THRU-THICKNESS BENDING STRESS DISTRIBUTION AT ELEVATED TEMPERATURES

A Thesis

by

LEE CONNER CHRISTIAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2005

Major Subject: Civil Engineering

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ABSTRACT

Thru-Thickness Bending Stress Distribution at Elevated Temperatures. (May 2005)

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During the bending of flange plate used for dapped girders some highway bridge fabricators are experiencing cracking of the flange plate particularly when heat is used in assisting the bending process. Due to the extreme strains experienced during the fabrication process, investigating this problem requires the use of a finite element analysis. The fabrication process was broken down into two parts, first the heating of the plate through the use of either a furnace or an acetylene torch (thermal), and the second was the bending process (structural). The five different temperatures collected during the thermal analysis were a uniform temperature of 75^{o}F, a 1100^{o}F uniform temperature as a result of furnace heating, both five and ten minutes of air-cooling after the plate had reached a uniform temperature of 1100^{o}F, and the temperature gradient after heating the flange plate to a surface temperature of 1200^{o}F though the use of an acetylene torch. After the thermal analysis was completed, the resulting temperatures were imported into the structural model. The plate thicknesses analyzed were one, one and a half, and two inches, assuming both 50 and 70 ksi yield strengths. To achieve a 90 degree six-inch radius bend the plate was bent in five separate locations. The result of this analysis showed that with the introduction of temperature gradients into the

fabrication process, the strains along the plate's extreme fibers increased. The model further showed that for both a one and a half and two-inch thick plate the extreme fiber strains exceeded ten percent, which further adds to the increased risk of the flange plate cracking during fabrication. The highest residual stresses through the plate's thickness occurred during cold bending. The residual stresses through the plate's thickness decreased when the fabrication process was carried out at elevated temperatures. When steel exceeds a strain of 10 to 16 percent during the fabrication process, the plate becomes susceptible to cracking. This strain limit was exceeded for plate thicknesses of one and a half and two inches.

DEDICATION

This thesis is dedicated to my parents Milton and Melodee, and my sister Kristi.

ACKNOWLEDGEMENTS

I would like to thank Dr. Peter Keating for the guidance that he has given me throughout this research project and Dr. Anne Raich and Dr. Harry Hogan for their willingness to be on the advisory committee and the contributions that they have made. This research project was made possible through the funding given by the Texas Department of Transportation.

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1. INTRODUCTION

1.1 Background

Steel plates are commonly used in the highway bridge industry to fabricate built-up girders that can span around horizontal curves and over longer distances than can not be accomplished with prestressed concrete beams. Large, mulit-level highway interchanges often employ both steel and prestressed concrete spans. The steel girders are usually deeper in cross section than the prestressed concrete beams due to the greater span lengths of the steel girders. The point of transition between the two types of spans requires the end of the steel girder to be reduced in cross section depth so that both the prestressed concrete beam and steel girder can be seated on a common bent cap. Figure 1-1 shows an example of a bent cap with both types of members. A steel girder with an end transition is commonly referred to as a dapped girder.

The reduction in girder depth is possible since the moment capacity requirements are less at the end of the span than other locations. Shear capacity requirements, though higher at the end of the girder, can still be met in the dapped region by stiffening or increasing the thickness of the web plate.

The use of dapped girders by the Texas Department of Transportation (TxDOT) has increased insignificantly over the past ten years as highway construction projects in

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urban areas have required more complex interchange designs. Several end transition details have been used by TxDOT for their dapped girders. Figure 1-2 shows a detail that requires extensive welding and stiffening. Consequently, its use has fallen out of favor. A more common detail is one in which the bottom flange is bent to form the transition, as can be seen in Figure 1-1, for example. Mechanically bending the flange plate about its weak axis is preferred, due to economic and performance reasons, over welding the plates together with a complete penetration groove weld to form a kink. The groove weld requires plate preparation prior to welding and nondestructive testing upon its completion. Additionally, the completed welded flange splice may still require bending to correct the transition angle for weld shrinkage and distortion.

The slope of the transition can range from 1:5 to vertical. The vertical, or 90-degree bend has been gaining popularity for aesthetic reasons. The bottom flange more closely follows the lower vertical face of the bend cap and minimizes the appearance of the transition. (This detail also simulates the appearance of a similar detail used for TxDOT's prestressed concrete U-beams.) An example of the 90-degree bend used at the end of a trapezoidal box or tub girder is given in Figure 1-3. The standard TxDOT detail calls for a 6-inch radius when the 90-degree bend is used.

Figure 1-1. Example of Bridge Bent Cap Supporting both a Steel Girder and Prestressed Concrete Beam (U.S. Highway 59 and Sam Houston Tollway Interchange, Houston, TX).

Figure 1-2. Example of Welded Dapped Girder Detail. (Sam Houston Tollway and Interstate 10 Interchange, Houston, TX)

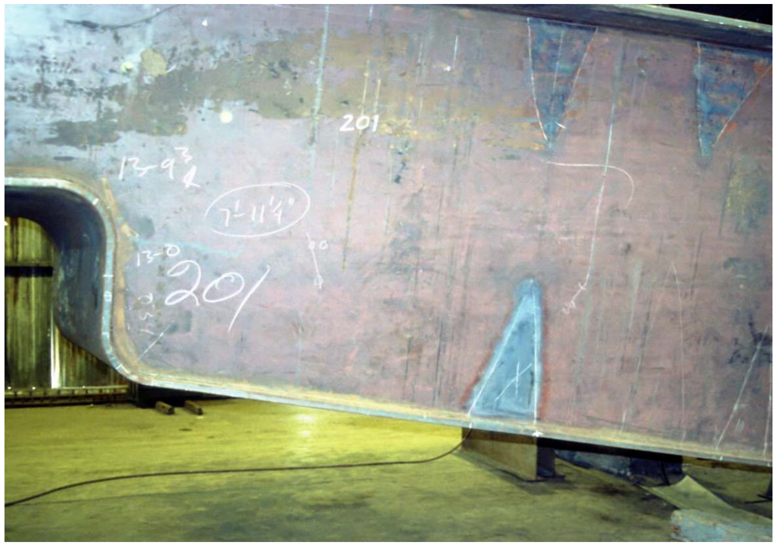


Figure 1-3. Example of Dapped Trapezoidal Box Girder during Fabrication. (for U.S. Highway 59, Houston, TX)

Depending on several parameters, such as flange thickness and width, bending angle and radius, and plate yield strength, the bending operation may involve several load-bending cycles as well as the application of heat. The actual process used to bend the plate is a function of fabricator equipment and preference. Heat is often used to reduce the bending strength of the steel when the required bend forces exceed the capacities of the fabricator equipment. This is common for trapezoidal box girders were the bottom flange width can exceed five or more feet.

The bending of the flange causes the formation of residual stresses and the possibilities of cracking due to the high strains experienced at the extreme fibers. Because of the cracking problem, the American Association of State Highway and Transportation Officials (AASHTO) specifications do not allow cold bending for fracture critical materials (AASHTO/NSBA 2002). This makes it necessary for dapped girders flanges to be bent at elevated temperatures for they are commonly designated as fracture critical. Cracking even at elevated temperatures is still a major concern, factors that play a role in the plate's susceptibility to cracking is how fast the plate is loaded and the temperature distribution thru the plate's thickness during the bending process. As the loading rate is increased so does the likelihood of cracking and local distortions occurring in the bent plate (AASHTO/NSBA 2002).

1.2 Problem Statement

Fabricators of dapped girders for TxDOT have occasionally experienced cracking of the flange plate during the bending process. Any formation of cracks during fabrication is cause for rejection of the plate and is therefore undesirable and costly. As part of an overall investigation of the plate bending process (TxDOT Research Project 0-4624), the study present herein focuses on an analytical study used to help quantify the residual thru-thickness stress and strain distributions that develop as a result of the bending process. This study is necessary to better understand the cause of the cracking and help develop measures necessary to prevent it.

Due to the excessive strains that result from the plate bending process, experimental data is difficult to obtain. Therefore, the Finite Element Method (FEM) will be used to develop an analytical model of the bending process. Two general areas of study will be conducted. First is the determination of the residual stress and strain distributions at normal fabrication temperatures (70 to 80ºF). The second area is study the effect of heat and cooling rates on these distributions. More specifically, the following will be investigated in the current study:

- The effects heat has on the extreme fiber strains as a result of the bending process.
- Residual stress distributions along the extreme fibers caused by various bending temperatures.
- Thru-thickness bending stress distribution of a plate that is fabricated by using multiple hits to obtain a 90 degree six-inch radius bend.
- The attenuation of strain along the plate's extreme fibers as a result of the bending process.

2. LITERATURE REVIEW

Fabricating steel plates by bending into various forms is common throughout the steel manufacturing industry. Because of this various standards have been developed over the years for guidance during the manufacturing process. It is important to have an understanding of the current industry standards and past research related to plate bending in order to have a starting point into what might be the cause of cracking of the bent flange plate of dapped girders.

2.1 Strain Limitations

It has been found that as steel is bent to different degrees of severity it becomes necessary at some point to heat-treat steel to recover some of the lost material properties. For carbon and low allow steel vessels, section UCS 79, of the ASME (2004) Boiler and Pressure Vessel Code five percent of extreme fiber elongation from the as-rolled condition is used to determine whether it is necessary to heat-treat steel upon completion of the bending process. The equation that is used by ASME Boiler and Pressure Vessel Code, in section UCS-79, to determine the plate's extreme fiber elongation for a single curvature is given by:

$$\%\ extreme\ \ fiber\ elongation = \frac{50t}{R_f}\left(1 - \frac{R_f}{R_o}\right) \quad \text{.................................. (Equation 2-1)}$$

where R_o is equal to infinity for flat plates. This five percent strain limit dates back to early steel manufacturing when steel had property degrading imperfections in higher concentrations than what is found in today's manufactured steel. Because of the improvement in the manufacturing process of steel some studies suggest that the five percent strain limit is to conservative and should be increased to as high as seven percent ((Bala and Malik 1983), (Blondeau et al. 1984)). The boiler and pressure vessel industry has not accepted this seven percent strain level, in part, because of the catastrophic consequences of failure.

Using Equation 2-1 for determining the extreme fiber strain it was found that bending a plate to a six-inch radius caused the extreme fibers to exceed the five percent strain limit proposed by the boiler and pressure vessel code, shown in Table 2-1. Equation 2-1 further indicated that the seven percent limit proposed for the use on steel having a cleaner metallurgical composition was also exceeded. So whether the ASME boiler and pressure vessel code is followed or the less stringent seven percent limit is observed a plate having a thickness of over one inch being bent to a six-inch radius requires some form of heat treatment after bending.

Table 2-1. Resulting Extreme Fiber Strains

Plate thickness (in.)	ASME Code
1	8.3
1.5	12.5
2	16.7

2.2 Residual Stresses

Residual stresses can occur when a material is loaded beyond the yield point into the inelastic region of the stress-strain curve. Upon unloading, those stresses that remain are the residual stresses. If a material deforms into the inelastic region it will undergo permanent deformation with the residual stresses being determined by taking the difference in the initial stress and the change in stress after unloading (Kervick and Springborn 1966).

$$\sigma' = \sigma - \Delta\sigma \quad \text{(Equation 2-2)}$$

The detrimental effects that residual stresses can have on a plate's mechanical properties are that residual stresses may be a source of cracking and stress corrosion. Residual stresses also reduce the apparent stiffness of the material as yielding occurs at lower stress levels upon reloading. The cracking and stress corrosion will occur where the tensile residual stresses on the inside surface of the plate bend are located (Weng and White 1990a). The zigzag distribution of residual stresses thru the plate's thickness after the plate is unloaded, shown in Figure 2-1, is common for any structural member with the magnitude of the residual stresses dependent on the bending loads.

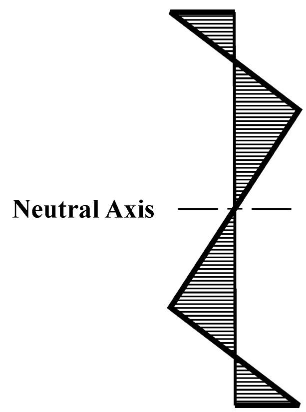


Figure 2-1. Residual Stress Distribution

When small bending radii are obtained from the bending process of a high strength structural steel, it has been observed that the compression side of the plate is thicker than that of the tension side. This causes the neutral axis to move from the centroid of the plat to as much as five percent of the plate's thickness (Weng and White 1990b). The movement of the neutral axis will cause an increase in the magnitude of stresses on the tension side of the plate. This increase is brought about by the fact that the sum of the stresses through the plate's thickness has to be equal to zero to produce stress equilibrium of the plate when the plate is free of external loads.

Another factor that plays a role in the amount of residual stresses that will occur after unloading of the plate is springback. Springback is the difference in the angle that the plate bent at maximum load and the angle the plate is observed at after unloading. Springback in practice makes it necessary to load a plate past the desired shape during the loading stage so that after unloading has occurred the plate will be bent to the correct position. A key part of calculating how much further a plate should be bent depends on the yield strength of the material. As the materials yield strength increases so does the materials springback after unloading. Another factor in determining the amount of springback the plate experiences is that as the bend radius becomes more sever the amount of springback occurring after the plate is unloaded decreases (Weng and White 1990b). This reduction in springback is caused by the decrease in the elastic portion of the bent plate. An equation for predicting the amount of springback after cold-bending is also referred to by Weng and White (1990b) as:

$$\frac{R}{r} = 4\left(R\sigma_y \frac{1-\mu^2}{Et} \right)^3 - 3\left(R\sigma_y \frac{1-\mu^2}{Et} \right) + 1 \quad \text{.......................................} \quad \text{Equation 2-3}$$

Where:

R = bend radius to the plate's neutral surface before springback. (inches)

r = bend radius to the plate's neutral surface after springback. (inches)

σ_y = yield stress (ksi)

E = Young's modulus (ksi)

t = thickness (inches)

μ = Poisson's ratio

With proper heat-treatment after the loading and unloading processes are completed the residual stresses can be reduced and the steel's original material properties can be restored.

2.3 Thermal Properties of Steel

The mechanical properties of structural steel change with a change in temperature. This may lead to changes in the stresses and strain distributions in both the loading and unloading cycles of the bending process. The major areas of concern when temperature is involved are the changes in the steel's stress-strain behavior, phase changes, and the thermal coefficient of expansion.

The stress-strain curve of steel plays an important role in determining the stresses and deformation that will occur for a given load. The stress-strain curves for steel change along with the change in temperature. Therefore, it is important to determine as accurately as possible the stress-strain curve for a particular steel grade. Experimental data is the best and most accurate way of determining the stress-strain curves for various temperatures but, unfortunately, it is not always possible to obtain that data. For this reason, several stress-strain-temperature relationships have been proposed. The most commonly used today in industry are the relationships proposed by Lie and the Eurocode. The Lie relationship, most widely used in North America, uses a bilinear curve to model the entire stress-strain curve (Lie 1992), while the Eurocode 3, most widely used in Europe, models the stress-strain curve with seven linear and parabolic equations (Poh 2001). There are other studies such as the one done by Poh that depicts the entire stress-strain-temperature behavior with a single equation (Poh 2001).

As steel increases in temperature it expands in all directions if the material is left unconstrained. If the expansion is confined, large compression stresses will develop. The coefficient for thermal expansion is generally accepted as 7.8 X $10^{-6}/^{o}F$ for fire analysis of structures (Cooke 1988) and this value is assumed to be constant as the temperature increases from room temperature to 1200^{o}F.

2.4 Heat-Straightening

Heat-straightening, or curving, is the use of heat to manipulate damaged steel into the desired shape without adversely affecting the material properties of the steel. This is commonly used in the bridge industry today to repair damaged bridge beams in the field as well as to correct welding distortion during fabrication. Important aspects of heat-straightening that have to be addressed are the pattern and temperature in which to heat the beam to, the method of applying the heat to the member, and the determination of whether or not restraining forces should be used.

Typical heating patterns for repairing damaged beams are (Avent 1992):

- Vee heating - used for straightening strong axis bends (see Figure 1-3, for example)
- Edge heating – used for making smooth and gentle plate bends
- Line heating – used for repairing a weak axis plate bend
- Spot heating – used for repairing localized bulges and dents in a plate

According to Avent (1989) when using these heating patterns it is important to apply the heat as evenly as possible and only to the region where plastic deformation has occurred so that when the beam is cooling the proper residual stresses will develop to obtain the desired outcome.

Temperature that the plate reaches during the process of heat-straightening should never exceed 1300^{o}F, for if the steel exceeds this temperature it is in danger of going through a phase change that would change the molecular structure of the steel from a body centered cubic to a face-centered cubic. This phase where the molecular structure becomes face-centered is commonly called the martensite phase, and it will increase the steels susceptibility to brittle fracture during repeated loadings (FHWA 1998). For this reason the AASHTO/NSBA steel bridge fabrication guide specification has limited the temperature that the steel can reach during the heating processes to 1200^{o}F to avoid this phase change (AASHTO/NSBA 2002).

When heat-straightening is being preformed, a major concern is that the temperature is achieved as rapidly as possible without buckling or overheating the material to allow for the proper contraction forces to occur when the plate is being cooled (TXDOT 2004). The recommended application method for applying heat during heat-straightening changes as the thickness of the material that is being straightened changes. For member thicknesses of less than one inch it is recommended that a single orifice be used to apply heat, but when the thickness of the steel exceeds one inch it is recommended that a rosebud be used for apply heat to a member (FHWA 1998).

3. FINITE ELEMENT MODELING

3.1 Approach to Developing the Finite Element Models

The fabrication of dapped girders will often necessitate the application of heat while bending the flange plate. This need arises from the prohibition of cold-bending flanges of fracture-critical members as well as limiting capacities of bending equipment of a particular fabricator. Consequently, it is important to investigate the effects elevated temperatures and thru-thickness temperature gradients has on the initial and residual stress distributions as well as the strains that occurred at the extreme fibers of the plate. To fully investigate the effects of heat two finite element models were developed. One model was used to investigate the thermal characteristics of steel while a second model investigated the mechanical behavior during the bending process. Two different heating methods were modeled to depict the two most common methods used in the fabrication process. One thermal model modeled the temperature distributions resulting from heating a steel plate in a furnace to a uniform temperature and then allowing natural convection to take place. The other thermal model was developed to depict the use of an acetylene torch for heating the plate to an appropriate surface temperature. The thermal models were solved first. The resulting temperatures then were imported into the structural model to determine the stresses resulting from temperature and the bending process.

3.2 Stress-Strain-Temperature Curves

The mechanical properties of steel vary greatly as the temperature increases. Because of this fact, several researchers have proposed various methods of determining stress-strain curves when there is a lack of experimental data. Some of the research and proposed methods include the work by Poh, Lie, and the Eurocode 3 ((Poh 2001) (Lie 1992)). The Poh stress-strain equation models the linearly elastic region, plastic plateau, and the strain-hardening portion of the stress-strain curve in just one equation. Doing so allows for ease in using computer programs for plotting the different stress-strain-temperature curves that would be used in the structural model. The equations that Poh derived correspond to the S.I. system and the constants that are used in these equations are applicable for structural steel. Due to the complexity of converting all of the equations constants, the temperature was inputted as Celsius and stresses, resulting from a specified strain, were converted from mega pascals to pounds per square inch. The equation that was proposed by Poh (2001) is shown in Equation 3-1.

$$\sigma = \frac{\varepsilon}{2|\varepsilon|}\left\{ a - |a| + \left[\frac{(\beta_2 - \beta_3)b}{\left(1 + \left|\frac{(\beta_2 - \beta_3)b}{\beta_5}\right|^{\beta_9}\right)^{1/\beta_9}} + \beta_3 b \right] \cdot \left[1 + \frac{|b| - |(b - 0.001)|}{0.001} \right] \right\} \quad \text{... Equation 3-1}$$

In order to use Equation 3-1, nine equations had to first be solved for in order to find the six variables that are needed in the stress equation. The equations used for solving these variables are given in Equation 3-2 through Equation 3-10.

$$a = \beta_1 |\varepsilon| + \beta_4 \quad \text{.......... Equation 3-2}$$

$$b = |\varepsilon| - \beta_8 - \frac{\beta_4}{\beta_1} \quad \text{.......... Equation 3-3}$$

$$\frac{\beta_1}{E_{20}} = \frac{-0.0014 \cdot T + 1.001}{\left(1 + |0.00274 \cdot T + -1.959|^5\right)^{0.2}} + 0.493 \quad \text{.......... Equation 3-4}$$

$$\frac{\beta_2}{E_{20}} = \begin{cases} \dfrac{0.01334 \cdot T + 7.6705}{\left(1 + |0.008 \cdot T - 4.6|^5\right)^{0.2}} + 0.00016 \cdot T - 1.6975 & when\, T \le 500\,^oC \\ \dfrac{\beta_1}{E_{20}} & when\, T > 500\,^oC \end{cases} \quad \text{..... Equation 3-5}$$

$$\frac{\beta_3}{E_{20}} = \frac{-0.00064 \cdot T + 0.03616}{\left(1 + |0.0222 \cdot T - 12.556|^5\right)^{0.2}} + 0.000004 \cdot T - 0.00038 \quad \text{.......... Equation 3-6}$$

$$\frac{\beta_4}{E_{20}} = \frac{-0.00125 \cdot T + 0.50625}{\left(1 + |0.003175 \cdot T - 1.2857|^5\right)^{0.2}} - 0.0002 \cdot T + 0.63425 \quad \text{.......... Equation 3-7}$$

$$\frac{\beta_5}{E_{20}} = \begin{cases} \dfrac{0.0074 \cdot T - 0.925}{\left(1 + |0.0133 \cdot T - 1.667|^5\right)^{0.2}} - 0.0024 \cdot T + 0.046 & when\, T \le 500\,^oC \\ \dfrac{\beta_4}{E_{20}} & when\, T > 500\,^oC \end{cases} \quad \text{... Equation 3-8}$$

$$\frac{\beta_8}{\left(\sigma_{20}/E_{20}\right)} = \frac{-0.05 \cdot T + 10}{\left(1 + \left|0.01 \cdot T - 2\right|^5\right)^{0.2}} + 5 \quad \text{……………………………………… Equation 3-9}$$

$$\beta_9 = \frac{-0.003 \cdot T + 1.125}{\left(1 + \left|0.0133 \cdot T - 5\right|^5\right)^{0.2}} + 0.001 \cdot T + 0.275 \quad \text{………………………… Equation 3-10}$$

The term β_1 can be solved for in Equation 3-4 for various temperatures and compared to the structural steel's modulus of elasticity that was found experimentally by Cooke (1988) shown in Table 3-1. Comparing modulus of elasticity's developed by Cooke to the ones proposed by using Poh's equation the error between the two was determined to be negligible.

Table 3-1. Comparing Modulus of Elasticity

	Modulus of Elasticity (ksi)		
Temperature (^{o}F)	Poh	Experimental	Error
68	29,000	30,800	5.8%
200	28,900	30,300	4.6%
800	25,400	26,700	4.7%

Further comparisons of the stress-strain curves had to be made in order to be sure that the best approach was being used for determining the stress-strain relationship when no experimental results were available. Even though research was conducted by Kirby and Preston (1988) for 50 ksi steel, only incomplete experimental data was given for comparing the analytical methods to experimental results. For this reason it was decided to not only compare the analytical results of a 50 ksi incomplete stress-strain curve, but in order to get a broader understanding for how correct these equations are it was also decided to compare the complete experimental data of ASTM A36 since the mechanical characteristics are similar to 50 ksi and 70 ksi steel.

Experimental data obtained by Harmathy and Stanzak (1970) for ASTM A36 structural steel was compared to the equations provided by Poh, Lie, and the Eurocode 3. Because the finite element analysis would later be run at similar temperatures, 75^{o}F and 1100^{o}F were chosen for comparing the different equations to the experimental results. Using Figure 3-1 to compare the stress-strain curves given by the experimental results to the three proposed equations for a temperature of 75^{o}F, it was observed that Poh equation yielded results closest to the experimental results. The Lie equations would not be a good estimation of the steels material properties because after the strain exceeds 0.05 (in./in.), the equation overestimates the stress while the Eurocode 3 underestimates the stress. Comparing the stress-strain curves at 1100^{o}F, as given in Figure 3-2, similar observations were made to that of the 75^{o}F curves.

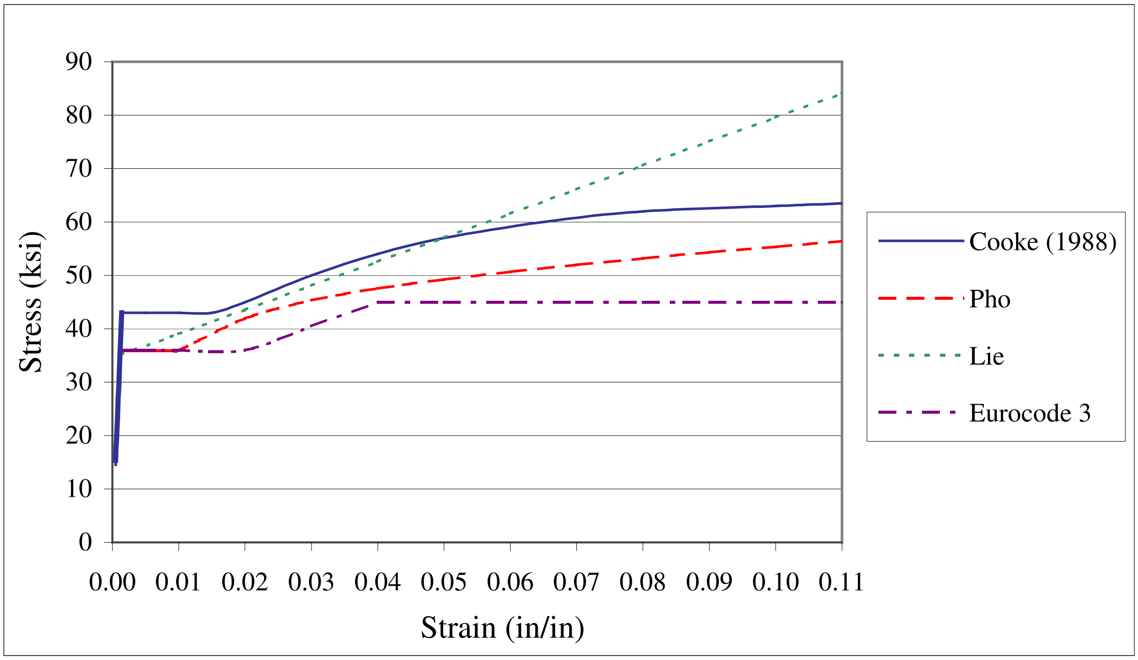


Figure 3-1. Comparing ASTM A36 Stress-Strain Curves at 75°F

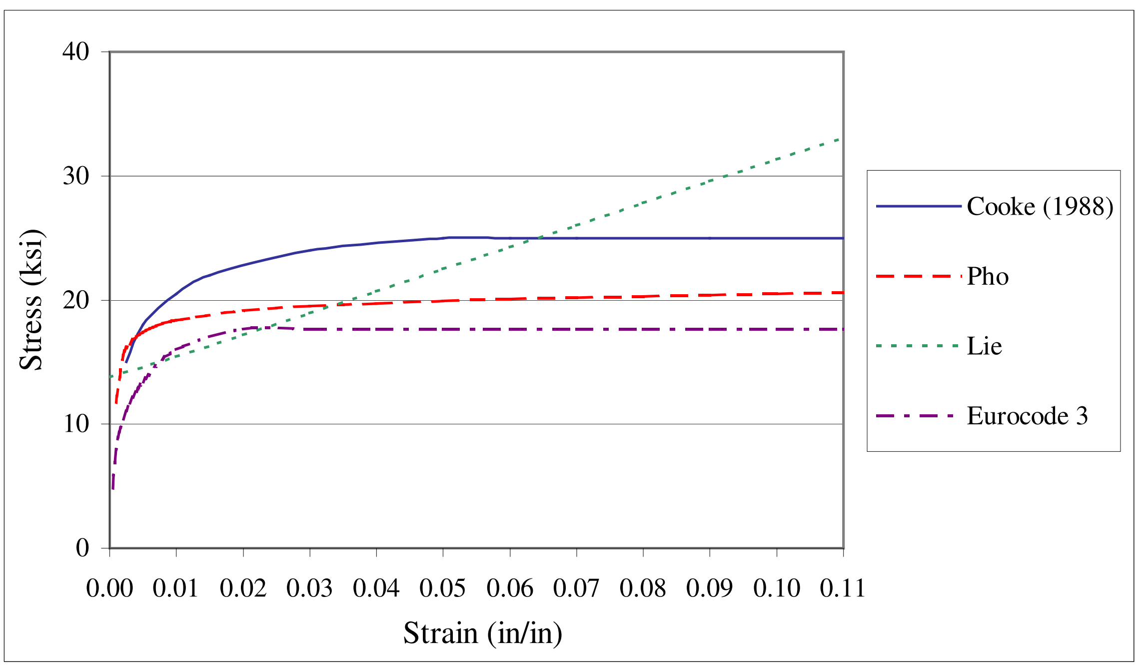


Figure 3-2. Comparing ASTM A36 Stress-Strain Curves at 1100°F

Comparing the analytical equations to the experimental data given by Kirby and Preston (1988) for 50 ksi steel, both the Poh and Eurocode 3 equations correlate well to the data found through laboratory testing for the plate at 68^{o}F, Figure 3-3. When the equations were compared for the plate at a higher temperature of 1112^{o}F, the Poh equation was not as conservative as the Eurocode 3 equations, Figure 3-4, but after looking at the data that was more complete for ASTM A36 at the higher strain ranges the Poh equations give a more conservative result. For this reason the most accurate method of predicting the behavior of the stress-strain curve for elevated temperatures was determined to be the equations proposed by Poh.

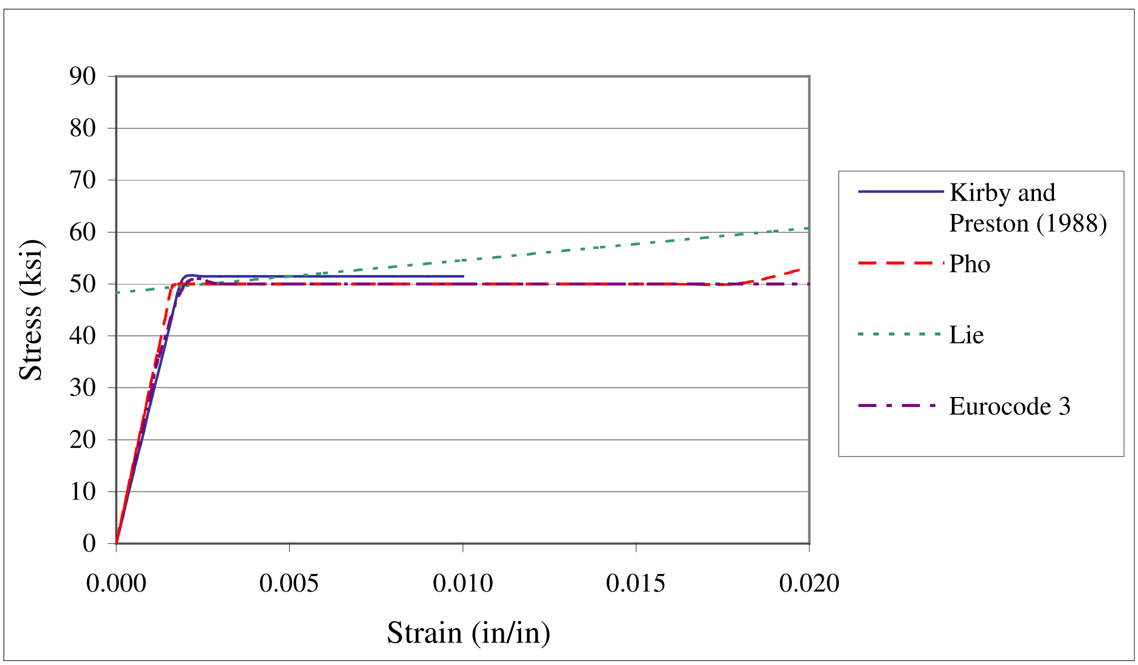


Figure 3-3. Comparing BS4360 Gr. 50 Stress-Strain Curves at 68^{o}F

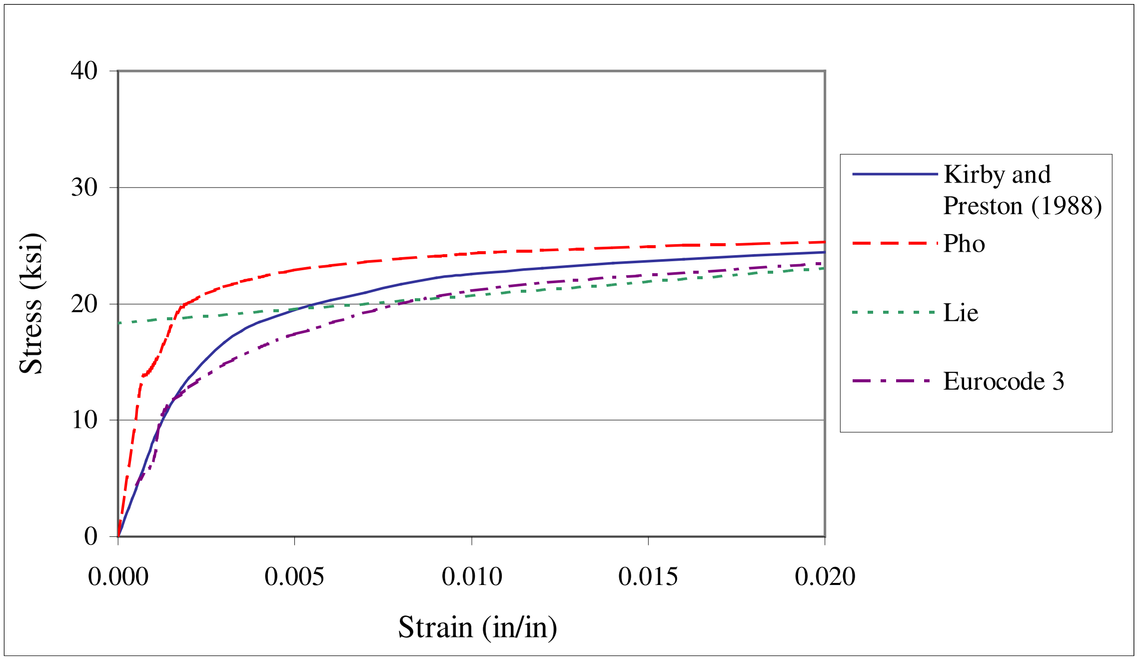


Figure 3-4. Comparing BS4360 Gr. 50 Stress-Strain Curves at 1112°F

3.3 Convection Model

Several assumptions were made for modeling the plate during cooling. The first assumption was that the plate would not be cooled by the forced convection but, rather, by natural convection and radiation. This assumption was made because in practice only natural convection is allowed until the plate is cooled below 600°F and then cooling can only be aided by dry compressed air (AASHTO/NSBA 2002). Another assumption was that the air temperature during cooling would be 80°F. In reality, the air temperature will vary depending on the climate in which the fabrication plant is located. The steel's thermal properties were assumed to be that of typical structural steel with the steel's thermal conductivity of $28.7\frac{Btu}{hr \cdot ft \cdot {}^{o}F}$ and its coefficient of heat transfer

$11.01\frac{Btu}{hr \cdot ft^2 \cdot {}^{o}F}$.

The steel plate that was modeled was assumed to be simply supported with its dimensions forty inches long and six inches wide. Therefore, internals stresses would not develop during cooling from support fixity. Different plate thicknesses were modeled to look at various temperature gradients that might occur during fabrication of flange plate. Figure 3-5, shows a typical representation of the thermal model and where the natural convection boundaries occurred. Quad 8 Node elements that were 0.2-inch square was used. Considering the elements as Quad 8 Node located a node every 0.10 inches along the model's faces so that the results would be more accurate than just a four-nodded element that would only determine results every 0.2 inches. It was assumed that the convection boundaries would occur only on the top and bottom surfaces of the plate. This assumption was made assuming that during fabrication the plate that is heated is at least several feet long and the bending occurs where there is little effect of the plate's end convection.

Preliminary finite element analysis was performed to investigate whether convection occurring at the ends of the plate would influence the results towards the inner length of the plate where the bending would take place. This investigation showed that the end convection only affected the thru-thickness temperature gradient with a few inches of the plate and could therefore be ignored. Subsequent temperature modeling ignored end convection altogether.

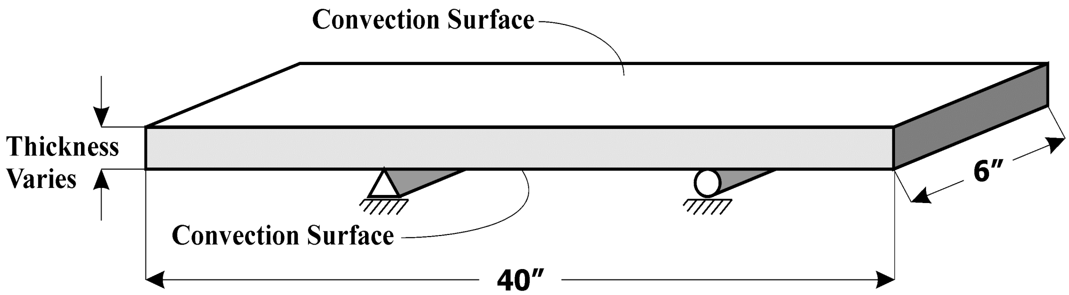


Figure 3-5. Convection Model

The model was to simulate what occurs after a plate is taken out of a furnace after a uniform temperature is achieved and then is allowed to naturally air cool. It was assumed that at the time the plate was removed from the furnace, the plate had reached a uniform temperature of 1100^{o}F. Temperature readings were taken after five and ten minutes of air-cooling. These times were selected to represent the time it would take for the plate to go from the furnace to the bend press and to induce the proper bend. The temperature readings would later be introduced into the structural model to simulate bending at elevated temperatures.

3.4 Conduction Model

In practice some fabrication uses acetylene torches to heat the steel to the desired temperatures prior to bending, Figure 3-6. This practice of using an acetylene torch heats the steel from the outside in so that the plate's surface is hotter than the inside of the plate. Because of this, the plate's behavior during bending could be different from the furnace heating method.

The steel's thermal conductivity was modeled as $28.7\frac{Btu}{hr \cdot ft \cdot {}^{o}F}$ with the plate's initial temperature assumed to be at a uniform temperature of 80^{o}F. The limiting temperature that the plate was allowed to reach was found in section 5.1 of the AASHTO/NSBA steel bridge fabrication guide specification S2.1-2002 as 1200^{o}F (AASHTO/NSBA 2002). Because of this limit, the conduction model was only allowed to achieve 1200^{o}F on the plate's surface before the heat source was removed. FHWA suggested method of applying heat to a plate that is over one inch thick is by using a rosebud tip (FHWA 1998). There is not a clear heating rate specified in codes for different fabricators will run the rosebud at different gas pressures and in different climatic conditions. Some manufacturers choose to use propane instead of acetylene to heat the plate before bending because propane is a safer gas to use and store. However, propane does not heat steel as quickly as acetylene does. For this reason, only the maximum temperature the plate can achieve at the end of the heating process is regulated. As the heating rate increases so does the temperature gradient through the plate's thickness. In Figure 3-7 different heating rates were modeled for a two-inch thick plate and the resulting temperature gradients were then plotted.

Figure 3-6. Acetylene Torch Heating

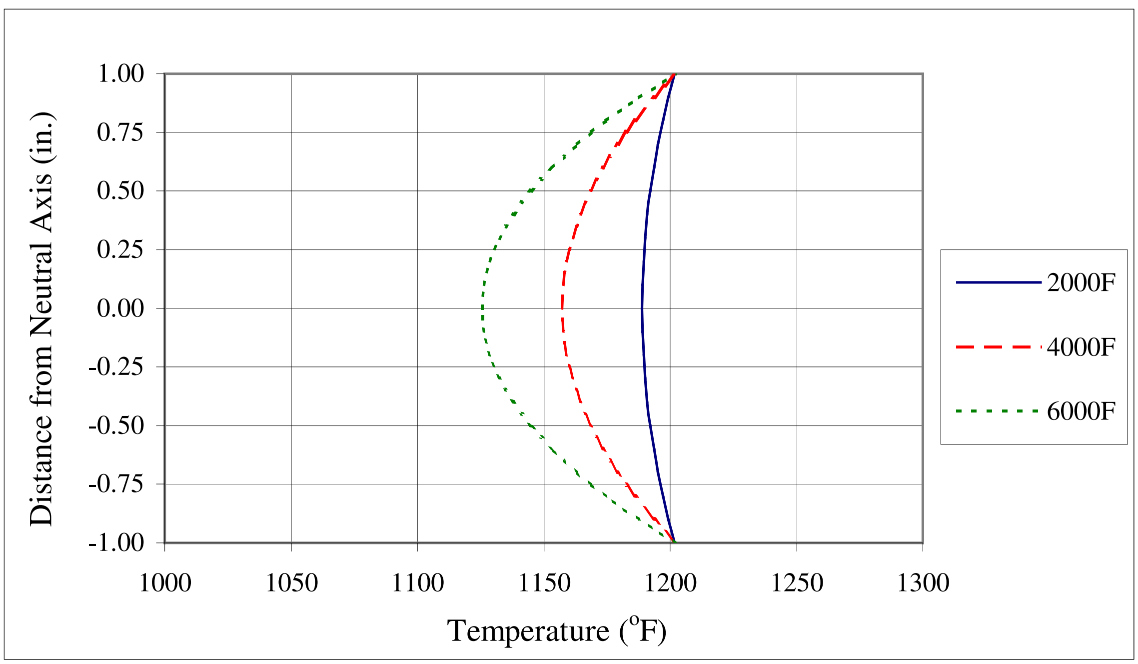


Figure 3-7. Comparing Heating Temperatures for 2-inch Plate

Because there is not too large of a difference in the temperature gradient with the different heating rates, all three heating rates were investigated by subjecting the model to a single-point bend and comparing the resulting thru-thickness stress distribution. The difference in stresses resulting from this comparison was insignificant, as shown in Figure 3-8. Therefore, it was decided that 4000^{o}F would be a close approximation to the torch's heating temperature during the fabrication of the flange plates. The small variation, at each temperature, in the steel's thru-thickness stresses can be explained by looking at the steel's stress-strain curve. As the steel increases in temperature, the slope of the curve in the plastic region becomes very small and closely resembles a bilinear curve. For this reason the steel after yielding will stay at a constant stress and will be unable to carry more load. Any additional loading will then have to be carried by material that has not yet yielded. Without consideration of thermal expansion the tensile and compression surfaces of the plate are equal in magnitude. With the introduction of thermal expansion, during elastic loading, the compression surface will be greater in magnitude than the tensile surface. As the bend becomes more severe, the stress at the mid-span of the plate starts to resemble a perfectly plastic stress distribution that cancels out any effect of the steel's coefficient thermal expansion. Since the flange plate may be bent at sharp bends and at high temperatures, the effect of the steel's coefficient thermal expansion is very small during the bending process.

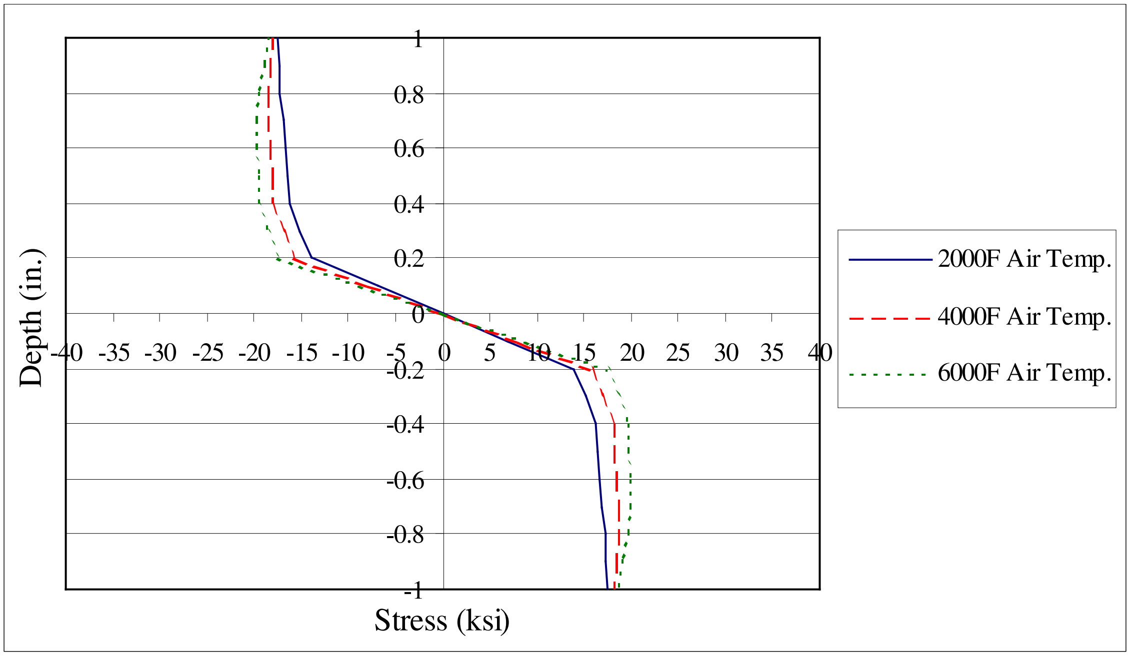


Figure 3-8. Comparing Thru-Thickness Stresses

For investigating convection effects, the steel was allowed to absorb heat through conduction boundaries along the plate's surface (Figure 3-9). To further model the heat that is generated by a rosebud's tip, the air above and below the top and bottom surfaces of the plate was at 4000°F simultaneously until the surface of the plate reached a temperature of 1200°F. The plate's dimensions were assumed to be the same as the plate that was modeled undergoing convection in the previous section.

The assumption that the plate is heated across the plate's entire surface is a simplification of the torch heating process. In reality the plate will only be heated in the region where the bend is to occur. But with the assumptions that bending occurs immediately after heating is completed with no convection allowed to take place, and that the fabricator will heat an area of two inches on either side of the bend location prior to bending the fabrication process is accurately depicted. The assumptions will have little effect on the resulting stress and strain distributions. The heating of the flange plate two inches on either side of the bend will later be shown to cause all of the resulting stress and strain distributions to occur in the heat affected region so little effect of the unheated plate will be present.

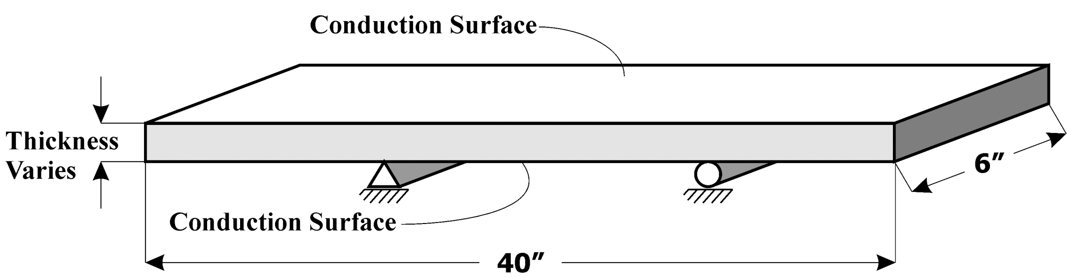


Figure 3-9. Conduction Model

3.5 Structural Model

Once the temperature effects were determined the temperature values were imported into the structural model so that the model could be bent at elevated temperatures. The structural model had the same dimensions as that of the thermal model with a line load located at the center of the plate, as shown in Figure 3-10.

The model was assumed to undergo plane strain with the stress-strain curves varying according to the temperature at various nodes. The stress-strain curves were inputted into the model as multi-linear curves. This is a valid representation of the stress-strain curve because as a curve is divided into small enough pieces it can be accurately represented by a collection of straight lines. When dividing the stress-strain curve up into parts for use in the multi-linear option in ANSYS 8.0, the slope of all lines has to always be positive. It was determined that if the model's temperature was in between two stress-strain curves ANSYS 8.0 would interpolate between the two curves to obtain a new stress-strain curve for that specific temperature. The coefficient of thermal expansion for steel was also added into the material properties so that the stresses caused by the difference in temperature could be added to the overall stress that the plate would undergo. The structural model was modeled with 0.2-inch square Quad 8 Node 82 elements so that the results would be determined every 0.1-inch along the elements faces (Figure 3-11). Using these nodes instead of a four-nodded element allowed for more accurate results.

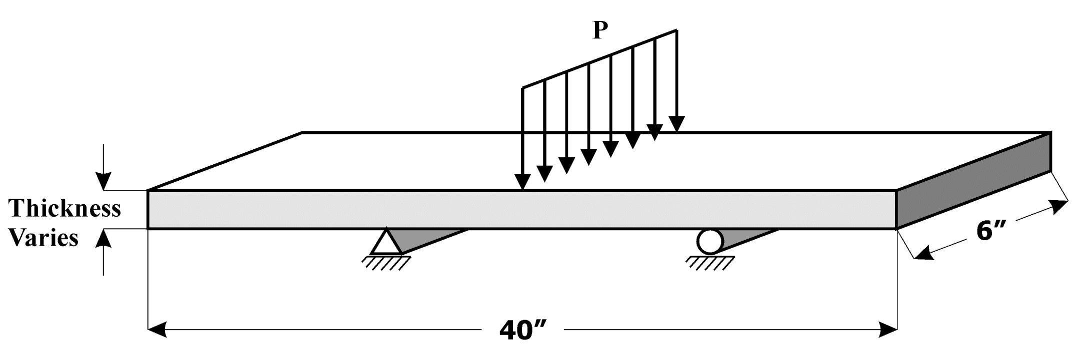


Figure 3-10. Structural Model

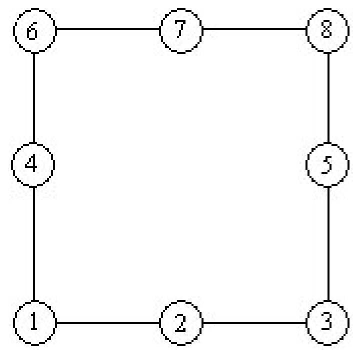


Figure 3-11. Quad 8 Node 82

3.6 Convergence Test

A convergence test was preformed on the structural model in order to determine if the model was refined enough or if elements needed to be added in order to achieve the desired accuracy. The model was run with three different element sizes of 0.2, 0.14, and 0.1-inch squares over the entire span of a ten-inch plate. The plate was loaded with 110 kips five inches from the end support and the plate's temperature was assumed to be 75^{o}F for each of the three test cases. For each of the three cases, the surface stress distribution was plotted in order to compare the accuracy of the model, shown in Figure 3-12. For all three test cases the stresses along the plate's surface were extremely close with the largest difference in stress occurring at the plate's midspan. The maximum difference in stress between the 0.14 and 0.1-inch mesh was 2.02 ksi, and the maximum difference between the 0.2 and 0.14-inch mesh was 0.22 ksi (Figure 3-13). When the plate was run using the finest mesh size, the run time was extremely long and would require even more time with the introduction of the variation in the plate's temperature. For this reason it was decided that the difference between the 0.1 and 0.2-inch mesh was acceptable. Therefore, the 0.2-inch square mesh size was used for the structural model.

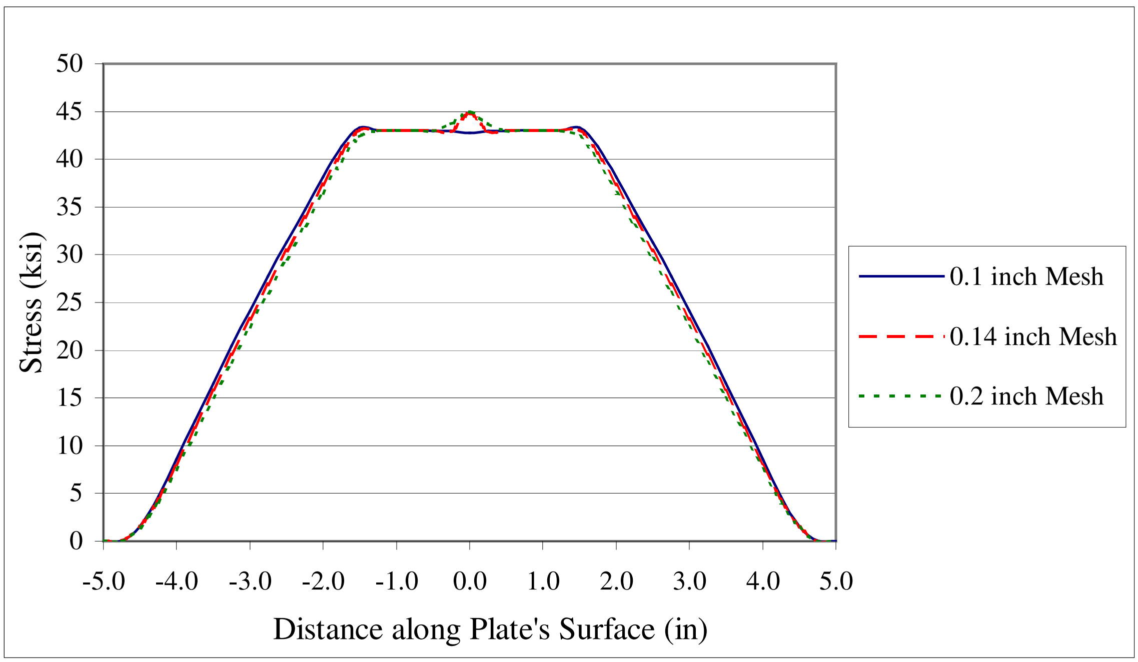


Figure 3-12. Comparing Surface Stress Distributions

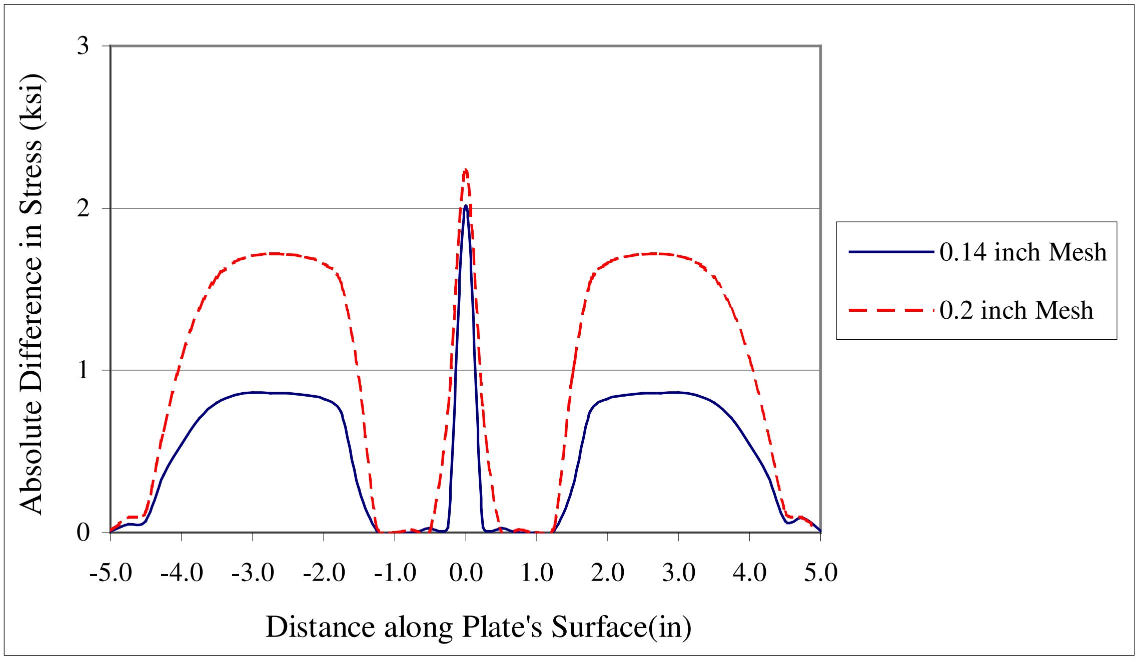


Figure 3-13. Comparison to 1/10 inch Meshing

4. THERMAL RESULTS

4.1 Thru-Thickness Temperature Gradients after Furnace Heating

Using plate thicknesses of one, one and a half, and two inches that are common in fabrication of bridge girders, a plate was simulated to undergo air-cooling once it was removed from a furnace after reaching a uniform temperature of 1100^{o}F. Thru-thickness temperatures were determined for a simulated air-cooling period of both five and ten minutes.

Five and ten minute temperature distributions were plotted at the plate's midspan for one, one and a half, and two inch thick plates. For the one-inch thick plate, the surface temperature cooled to 803^{o}F after five minutes and 565 ^{o}F after ten minutes. The difference in the surface temperature and the plate's mid-thickness was found to be 5.5^{o}F after five minutes of cooling and 4^{o}F after ten minutes of cooling, as shown in Figure 4-1. The small thru-thickness temperature gradient can be attributed to the relatively thin plate thickness.

The 1.5-inch thick plate surface temperature cooled to 885^{o}F after five minutes and 691^{o}F after ten minutes. The difference in the surface temperature and the plate's mid-thickness was found to be 9^{o}F after five minutes of cooling and 7.5^{o}F after ten minutes of cooling. As shown in Figure 4-2, the surface temperature decreases 194^{o}F after ten minutes of cooling from the temperature that was found after five minutes of cooling (885^{o}F). This decrease in temperature plays an important role in the amount of residual stresses that will result from bending for the mechanical properties of the steel increases as the temperature decreases.

For the 2-inch plate thickness, a temperature gradient of 13^{o}F occurred after five minutes of air-cooling and 12^{o}F after ten minutes of air-cooling (Figure 4-3). The surface temperature cooled to 937^{o}F after five minutes and 794^{o}F after ten minutes.

In all the plate sizes investigated, there was a small change in the temperature gradient for both the five and ten minutes of air-cooling. However, there is a large difference in surface temperatures at which the plate will undergo the bending process for the various plate thicknesses. Because of the cool down from an 1100^{o}F uniform temperature, the resulting residual stress and strain distributions will be affected.

The temperature gradients resulting from air-cooling the plate for five and ten minutes were imported into the structural model to simulate the bending of a plate after it has undergone furnace heating.

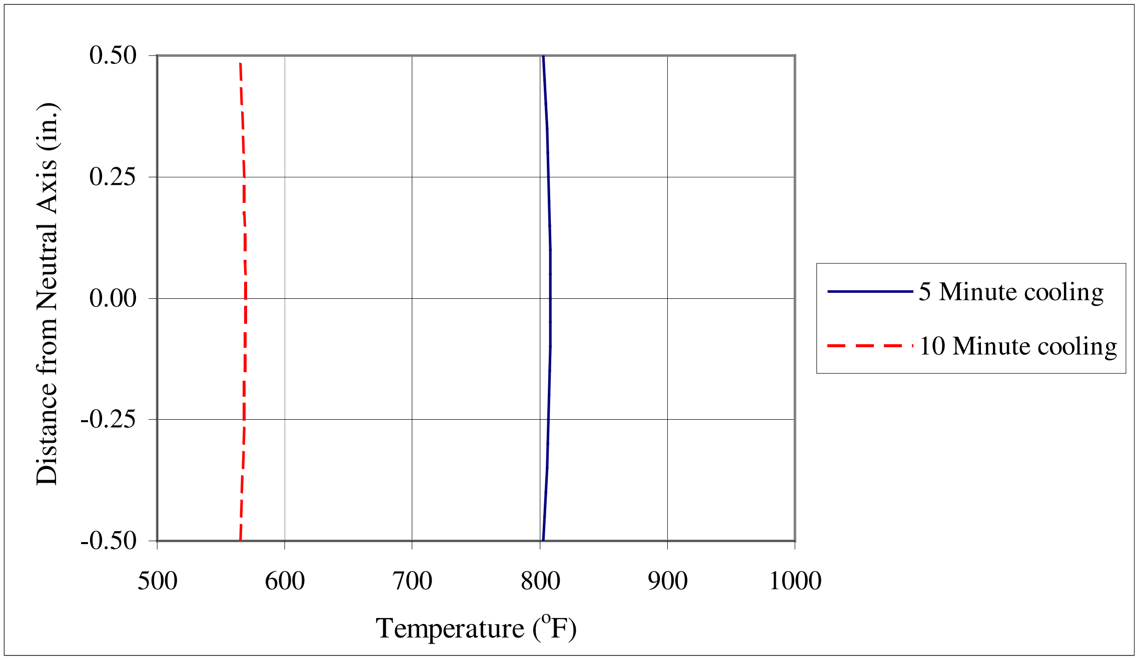


Figure 4-1. Thru-Thickness Temperature Distribution for 1-inch Plate

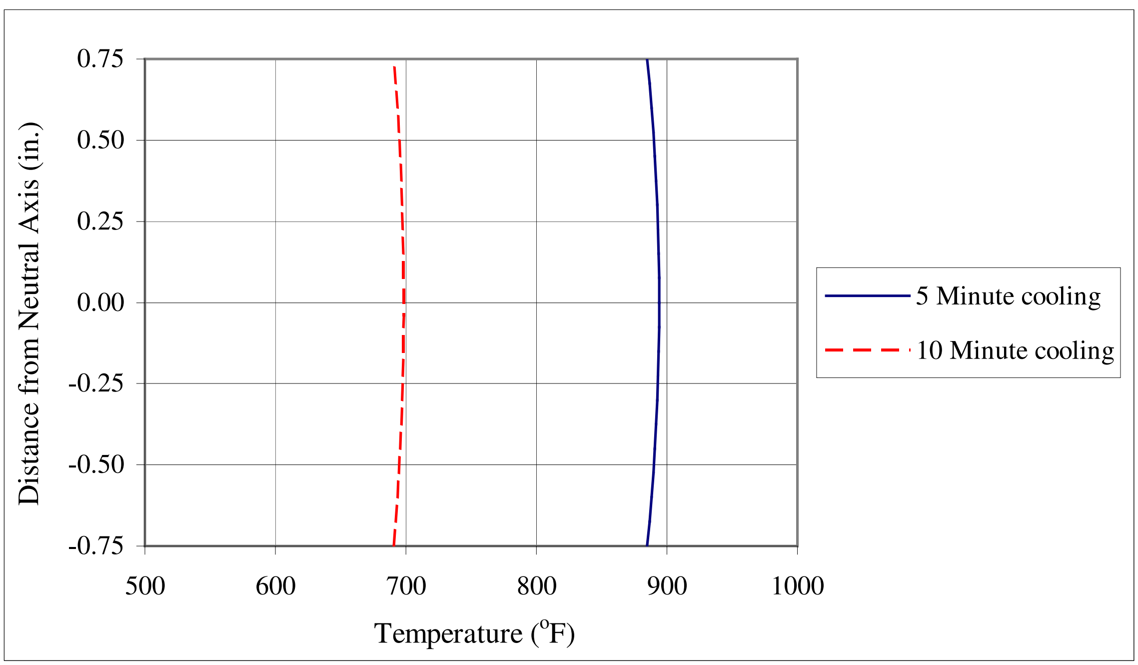


Figure 4-2. Thru-Thickness Temperature Distribution for 1.5-inch Plate

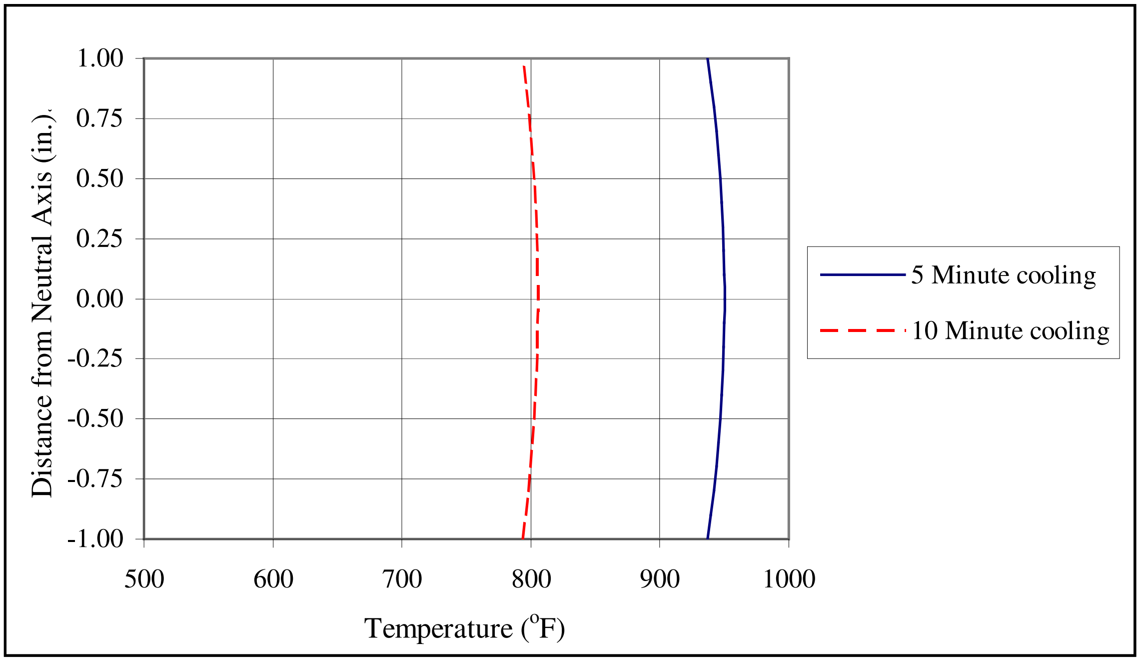


Figure 4-3. Thru-Thickness Temperature Distribution for 2 inch Plate

4.2 Acetylene Torch Temperature Gradients

Instead of heating the plate uniformly to 1100°F in a furnace, heating of the plate using an acetylene torch was also simulated. This results in a non-uniform temperature gradient prior to the cool down period and could therefore exaggerate the final or residual stress or strain distributions. During the heating process, the extreme fibers would be expected to go into compression due to their expansion relative to the inner fibers.

A conduction model was developed and the resulting stress distributions were found for a one, one and a half, and two-inch plate. In general, as the plate increases in thickness, the resulting temperature gradients increase as well as the amount of time required for the plate's surface to reach 1200^{o}F. In Figure 4-4, the resulting temperature gradient caused by torch heating is shown for a two-inch plate. Heating the ends of the plate during torch heating was determined to only affect the temperature gradient within a few inches of the end and it was determined that bending would not occur in this region during the fabrication of the flange plate.

The time that it took for a one-inch plate to go from a uniform temperature of 75^{o}F to having a surface temperature of 1200^{o}F was 4 minutes and 35 seconds when the air temperature along the top and bottom surface was at 4000^{o}F. It was assumed that heating took place simultaneously from both sides of the plate. Therefore, the time is less than that required if a single torch was used to heat the plate. The resulting difference in temperature from the plate's outside surface to it neutral axis, shown in Figure 4-5, was found to be 22^{o}F. The plate surface at the end of the heating process was 1206^{o}F, which was 6^{o}F larger than what the plate's surface temperature was desired to be but it was decided that 6^{o}F would not make a significant difference in the bending results.

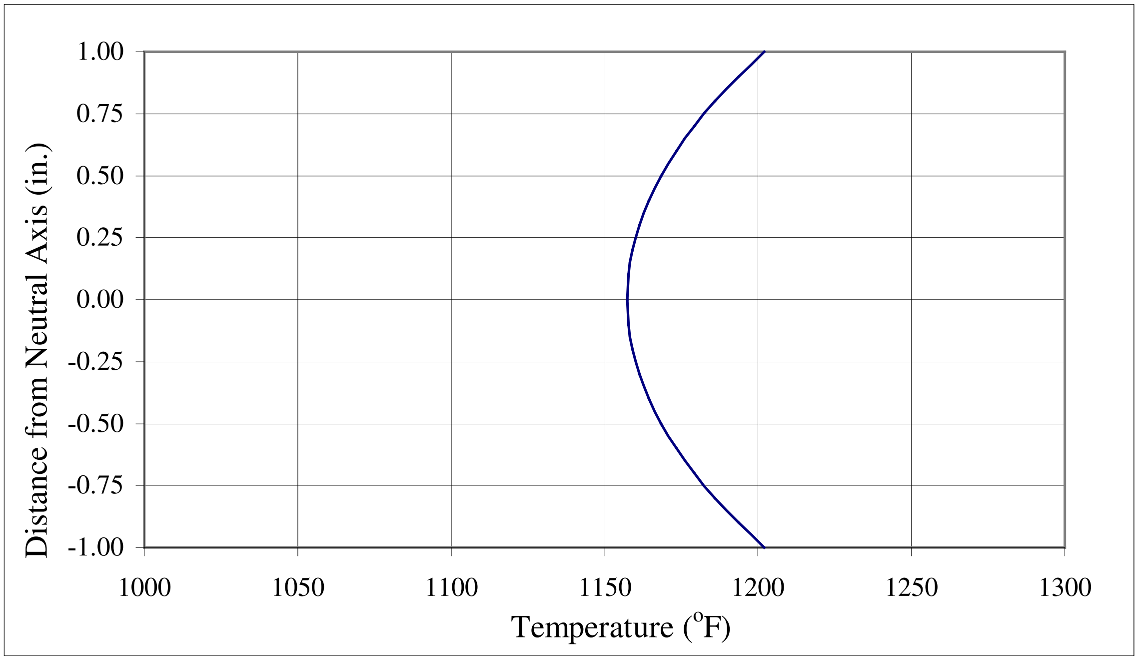


Figure 4-4. 1200°F Surface Temperature 2-inch Plate

The one and a half inch plate was found to have an increased temperature gradient from that of the one-inch plate, which was a result of the heat taking longer to be flow from the plate's surface to its inner core due to the increased thickness. The temperature gradient for a one and a half inch plate, shown in Figure 4-6, was 34°F, which was an increase of 10°F from that of the one-inch plate. The surface temperature of the one and a half inch plate after the heating process was completed was 1200°F. As the plate thickness further increased to two inches the temperature gradient became 44°F, Figure 4-4, with the amount of time that it took the plate to reach this temperature being longer than what was required for ether the one inch or one and a half inch plate.

The temperature gradients resulting from torch heating were imported into the structural model to simulate the bending of a plate as if it was originally heated by means of a torch.

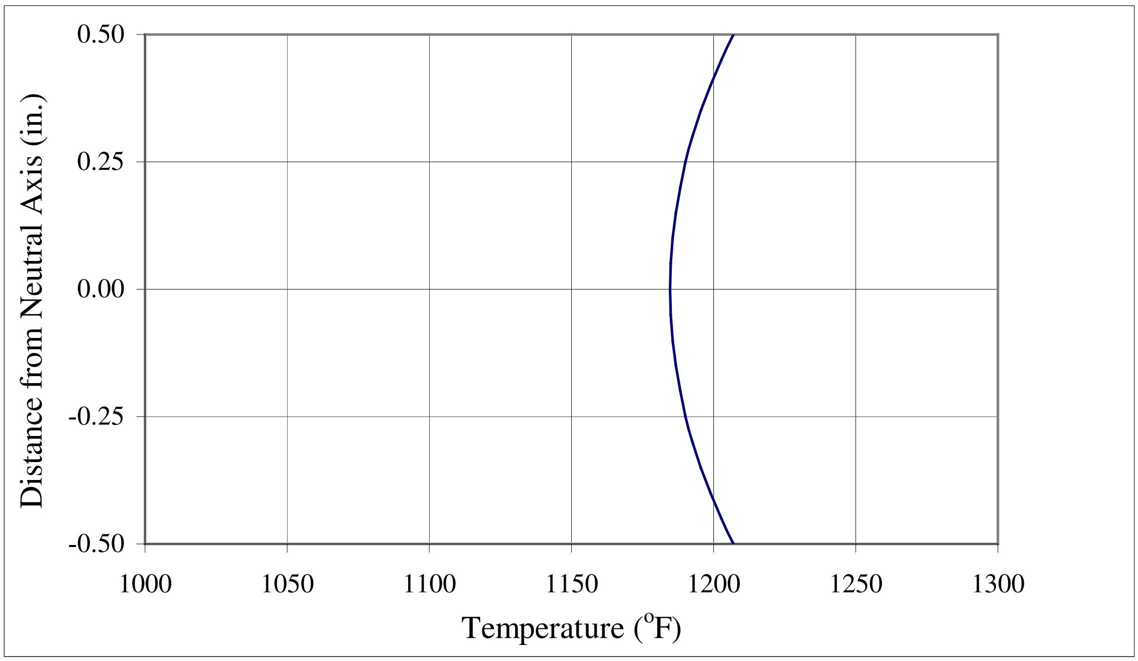


Figure 4-5. Acetylene Torch Thru-Thickness Temperature Distribution - 1 inch Plate

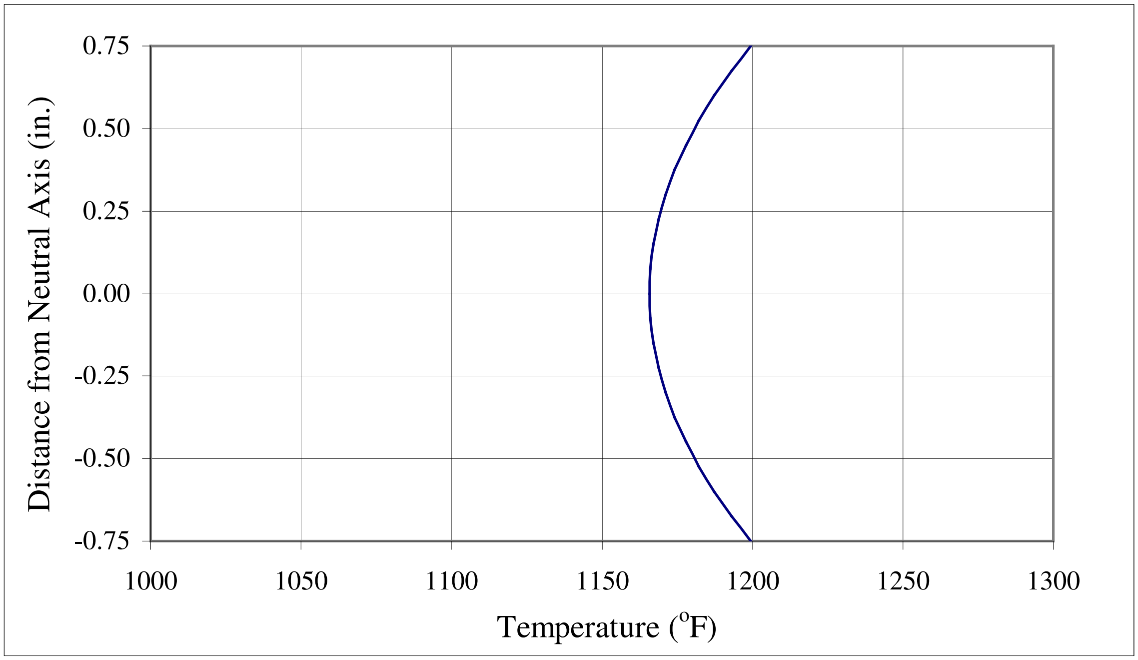


Figure 4-6. Acetylene Torch Thru-Thickness Temperature Distribution - 1.5 inch Plate

4.3 Comparison of Heating Methods

When comparing the temperature gradients obtained by the two different heating methods, it was determined that the two different heating methods created temperature gradients opposite each other. The furnace heating method allowed for the coolest portion of the plate to occur at the plate's surface where when heating through the use of a torch the coldest region in the plate was observed at the plate's centroid. When a torch was used during the fabrication process, the resulting temperature gradients at the time of bending were greater than that of a plate that underwent furnace heating. If the plate was allowed to cool after an acetylene torch was used, the temperature gradients in the plate would come to resemble the convection gradients. This is a result of steel radiating heat into the air faster than heat can be transmitted through the plate's thickness. When a torch is used in heating the plate to a surface temperature of 1200^{o}F the temperature at all points in the plate were higher than the initial temperature of the plate that under went furnace heating. This results in the plate following a stress-strain curve that is of smaller magnitude to the one that the convection plate follows.

5. STRUCTURAL RESULTS

5.1. Stress-Strain-Temperature Curves

Highway girders are commonly fabricated using 50 ksi and 70 ksi structural steel. Each of these grades of steel have mechanical properties that change with temperature, and it is important to have an accurate representation of these changes in order to have a correct understanding of what occurs in the material during the different load stages in a bending operation. In Section 3.2, the equations proposed by Poh (2001) were determined to be the most accurate and conservative representation of the steels mechanical properties when there is no available experimental data. Using these equations, stress-strain curves were found for grade 50 steel, Figure 5-1. It was decided that even though ANSYS 8.0 will interpolate between the various stress-strain curves the equation proposed by Poh would be used to create a series of stress-strain curves that would be in the temperature range under investigation. The same procedure was used to create the 70 ksi stress-strain-temperature curves that are shown in Figure 5-2.

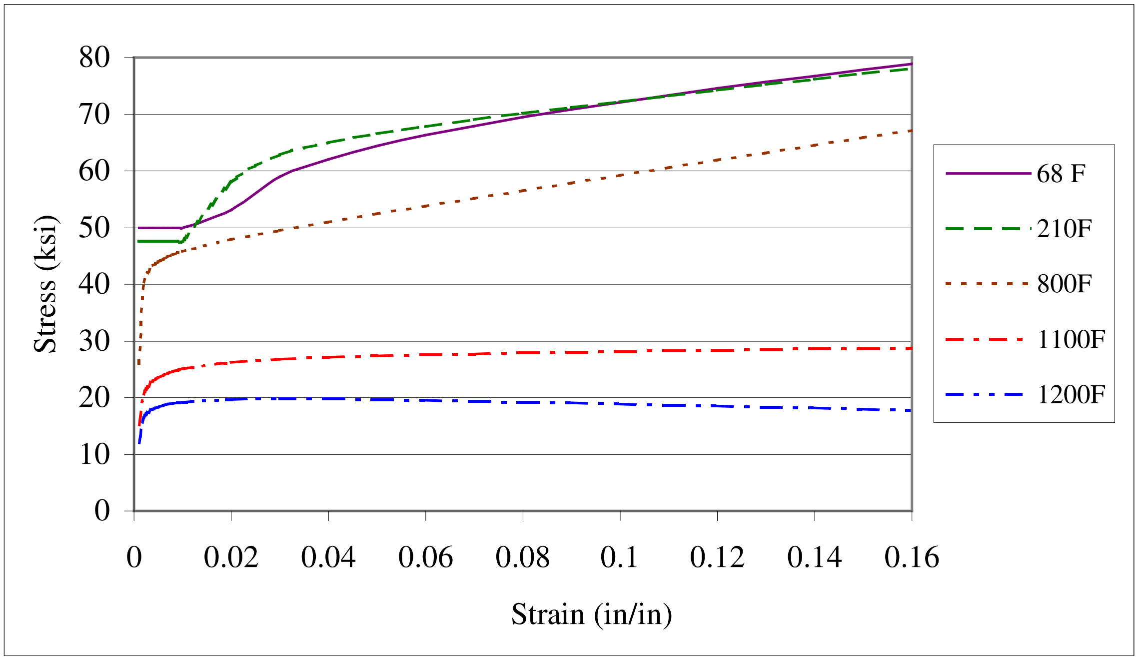


Figure 5-1. Grade 50 Stress-Strain-Temperature Curves

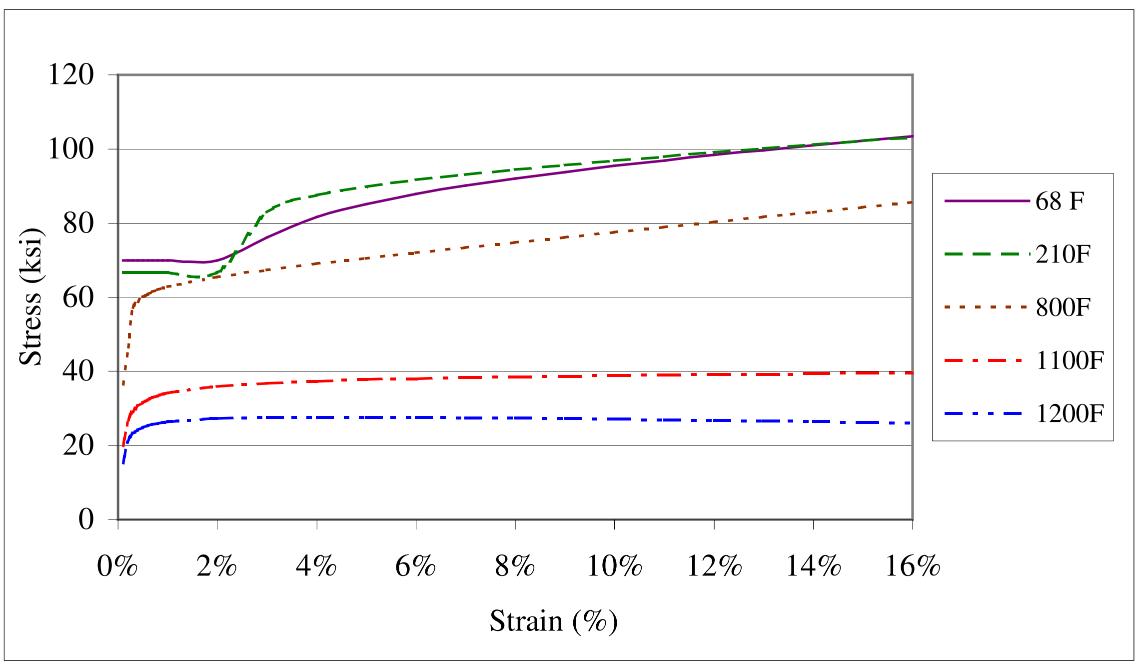


Figure 5-2. Grade 70 Stress-Strain-Temperature Curves

5.2. Six Inch Radius Bend

In dapped girder fabrication, a typical radius used to bend the flange plate is six inches. Some fabricators that use this bend radius are experiencing the formation of cracks during the bending process. A finite element model was developed to investigate and predict the level of thru-thickness residual stresses and strains that formed as a result of the bending process and determine what effects the application of heat might have on these distributions.

Due to the severity of the strains and the need to achieve a constant six-inch radius, multiple bend points must be used. There are no set specifications on exactly how many hits are to be used and how far apart the hits are to be from one another. It was decided to model the plate as simply supported with a total of five different loadings at one-inch intervals. As the line load moved across the plate the supports moved with it so that the load would always be applied at the midspan. Since the displacements of a 90-degree bend are so large, only a four-inch segment of the six-inch radius was modeled. This was deemed expectable for it was observed that during the bending process, stresses and strains as a result of bending remained relatively constant throughout the length of the bend. In Figure 5-3, the bending locations for the first three loadings are shown along with the final step that shows the correct bend radius along a four-inch segment.

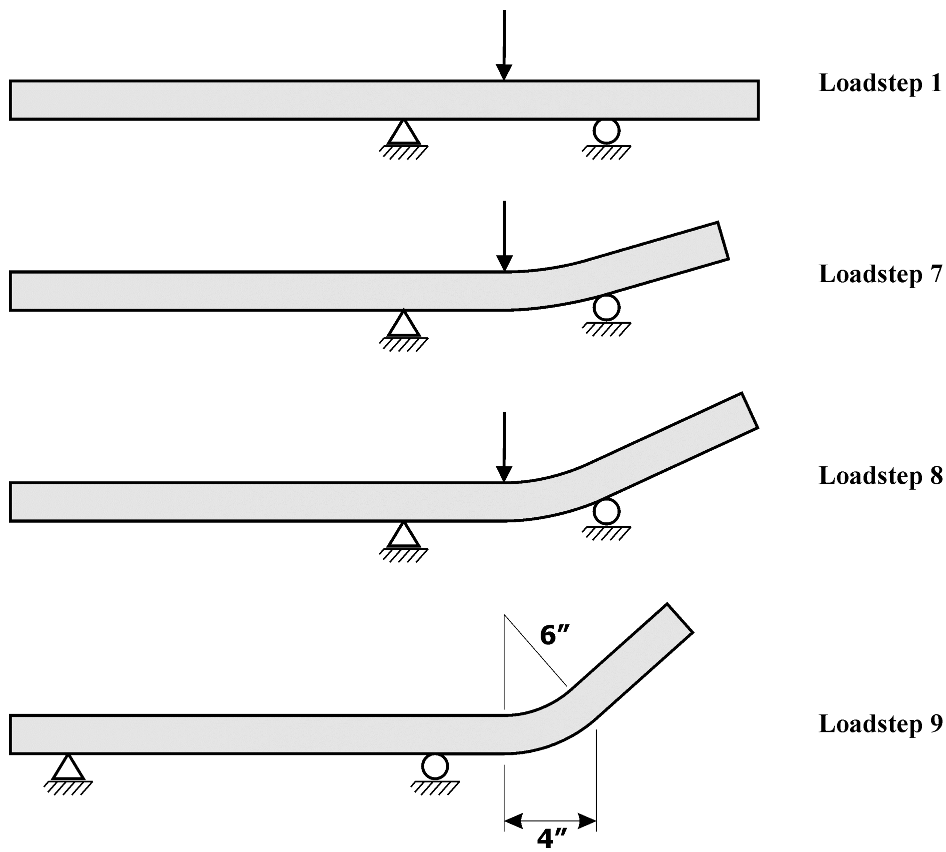


Figure 5-3. Load Steps

5.2.1. Surface Residual Stress Distribution

The magnitude of surface residual stress that occurs during the fabrication of the bent flange has a large part to do with the temperature of the plate at the time of bending. In Figure 5-4, the lowest magnitude of surface residual stresses occurred when the plate was heated using a torch to a surface temperature of 1200°F. The highest magnitude of surface residual stress occurred when the plate was bent at room temperature. This result directly relates back to the stress-strain-temperature curves that were developed in Section 5.1; as the temperature increases the amount of stress that can occur in the material decreases. Therefore, the resulting surface residual stress will also decrease with respect to temperature. In Figure 5-4, it is also seen that the residual stresses caused by allowing the plate to air cool for both five and ten minutes substantially increases the amount of surface residual stress in the plate to nearly the level that is seen at room temperature bending. This higher magnitude of surface stress from that of the 1100°F uniform temperature can cause the plate to have an increased chance of developing cracks. This increase in surface residual stress after five and ten minutes of air cooling can also be seen in the one and a half and two inch plate thicknesses that were studied, Figure 5-5 and Figure 5-6 respectively. As the thickness of the plate increased from one inch to one and a half inch, the surface residual stress after cold bending increase 8 ksi along with an increase in the ten minute residual stress of 3.5 ksi. Comparing Figure 5-4 to Figure 5-5, it can be seen that the 1100°F uniform temperature and the 1200°F surface temperature increased slightly. One reason for this small increase in the surface residual stresses is due to the fact that the stress-strain curve at both 1100°F and 1200°F are close to bilinear. This allows an increase in the strain while the stress in the material remains relatively constant. In Figure 5-6, the residual stresses for a two inch thick plate is shown with the same pattern of an increase in residual stress as the plate is bent at the various temperatures.

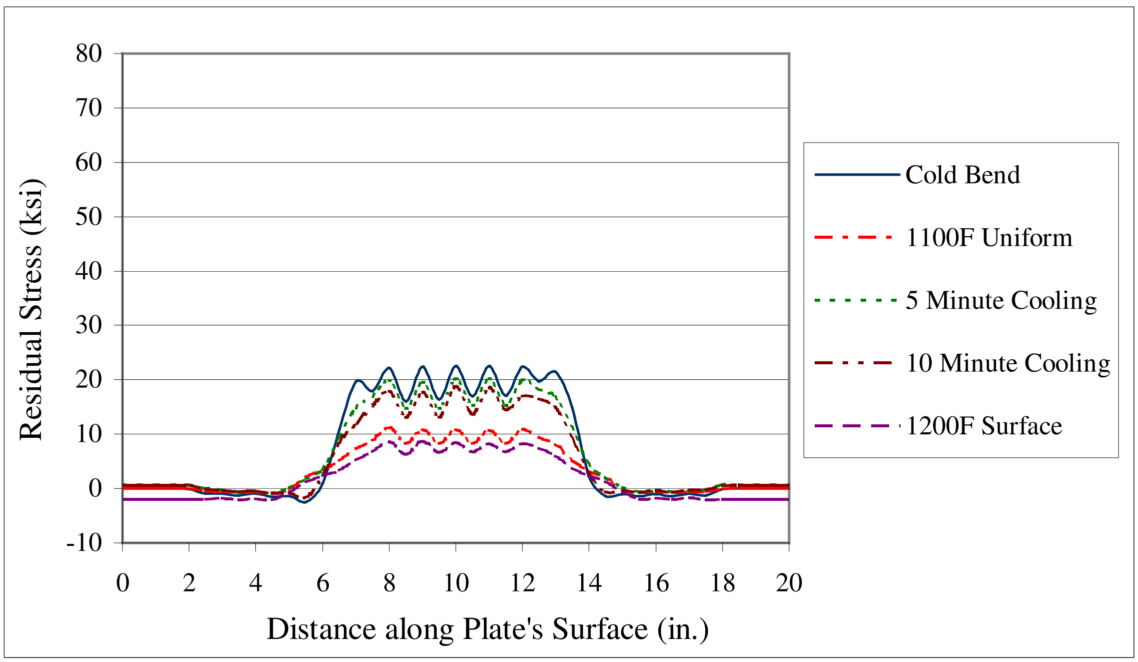


Figure 5-4. Surface Residual Stress 1 inch Plate - 50 ksi

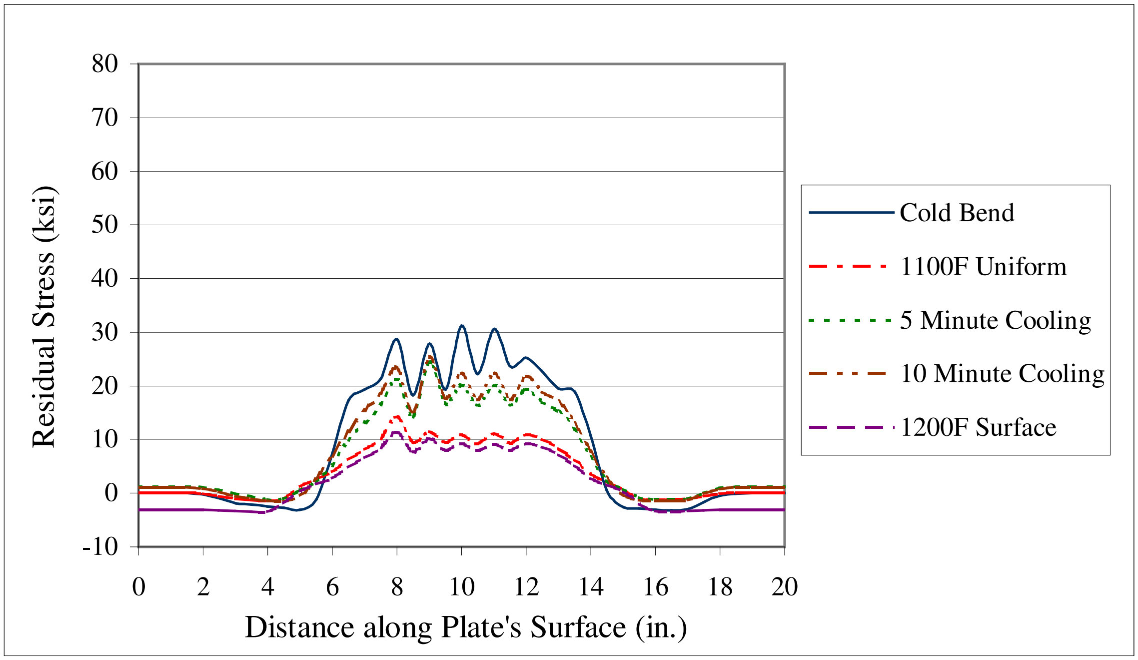


Figure 5-5. Surface Residual Stress 1.5 inch Plate - 50 ksi

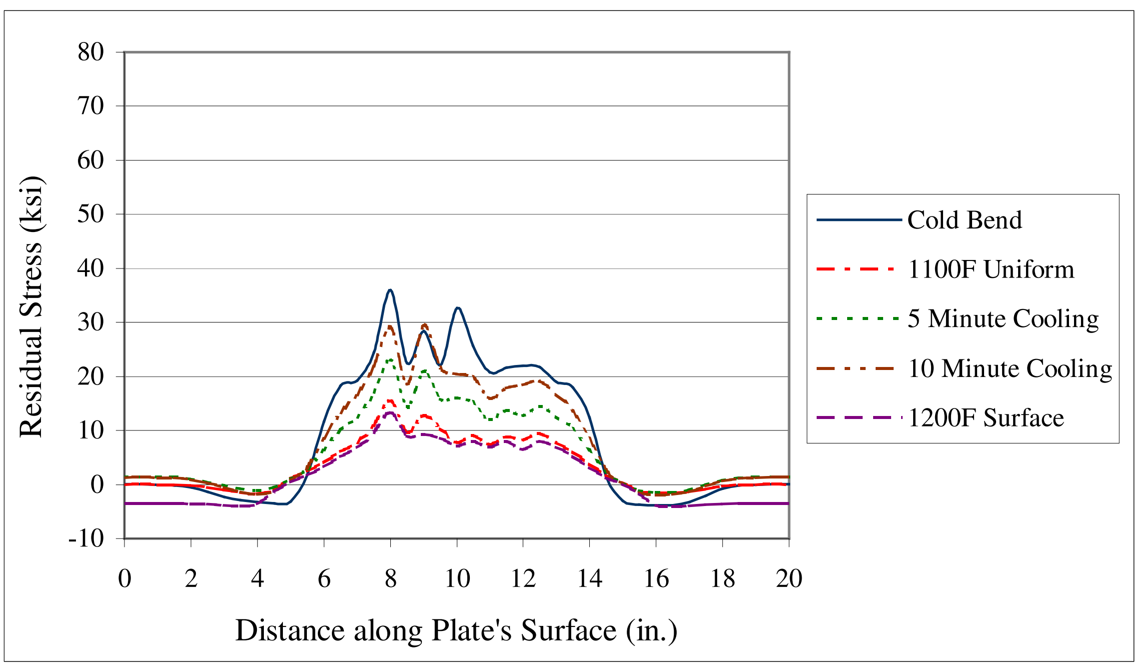


Figure 5-6. Surface Residual Stress 2 inch Plate - 50 ksi

5.2.2. Strain Along the Plate's Surface

The amount of surface strain that is present in the plate after it is bent is related to the severity of the initial bend, which is directly related to the degree of springback occurring in the plate after the load is released. Another factor is the plate's thickness. One equation given by the ASME (2004) Boiler and Pressure Vessel Code, (Section UCS-79), relates the thickness of the plate to the extreme fibers elongation (Equation 2-1). Other equations, such as Weng and White (1990a), discuss different equations that can be used for the determination of the magnitude of surface strain that can occur due to a curtain bend radius (Equation 5-1). The use of these two equations will provide a check of the finite element model to determine if the results between these equations coincide with the results that are given by ANSYS 8.0. In Table 5-1, the extreme fiber strains determined by the finite element program were compared to the equations in the boiler and pressure vessel code and the equation cited by Weng and White (1990a). The average strain along the plate's surface affected by the bending was found to be very similar to the predicted values with the greatest difference being 1.4 percent. Since the difference in the predicted values given by the two equations and the values obtain from ANSYS were so similar it was determined that the finite-element-model could be considered correct within reasonable error.

$$\%\ extreme\ \ fiber\ elongation = \frac{50t}{R_f}\left(1 - \frac{R_f}{R_o}\right)$$ ………………………………. (Equation 2-1)

$$\in_{\max} = \frac{1}{1.8\frac{R}{t}+1}$$ ……………………………..……………………..……. (Equation 5-1)

Table 5-1. Comparison of Surface Strains

Plate thickness (in.)	ASME Code (%)	Weng and White (%)	ANSYS 8.0 (Cold Bend) (%)	Difference from ASME Code (%)	Difference from Weng and White (%)
1	8.3	8.5	7.1	1.2	1.4
1.5	12.5	12.2	11.5	1.0	0.7
2	16.7	15.6	15.6	1.1	0.0

The surface strains in Figure 5-7 for the one-inch thick plate are shown to only extend two inches beyond the first and last loading of the plate with peak strains occurring at each of the five loading points. If the fabricator is slightly off of the six-inch radius bend, the amount of residual strains that the plate experiences can be greatly influenced by the fact that the loading of the plate takes the steel into the plastic region of the stress-strain curve. Therefore, a small change in the materials stress can greatly affect the amount of strain that will occur. For this reason, all plates were modeled to be within 1/10 of an inch to the correct radius at all points. The results for the one and a half inch plate are shown in Figure 5-8 and the results of the two-inch plate being bent to a six inch radius is shown in Figure 5-9. Each of these graphs follows the same behavior that was described for the one-inch plate thickness with only the strain changing 4 to 8 percent in magnitude between the plate thicknesses.

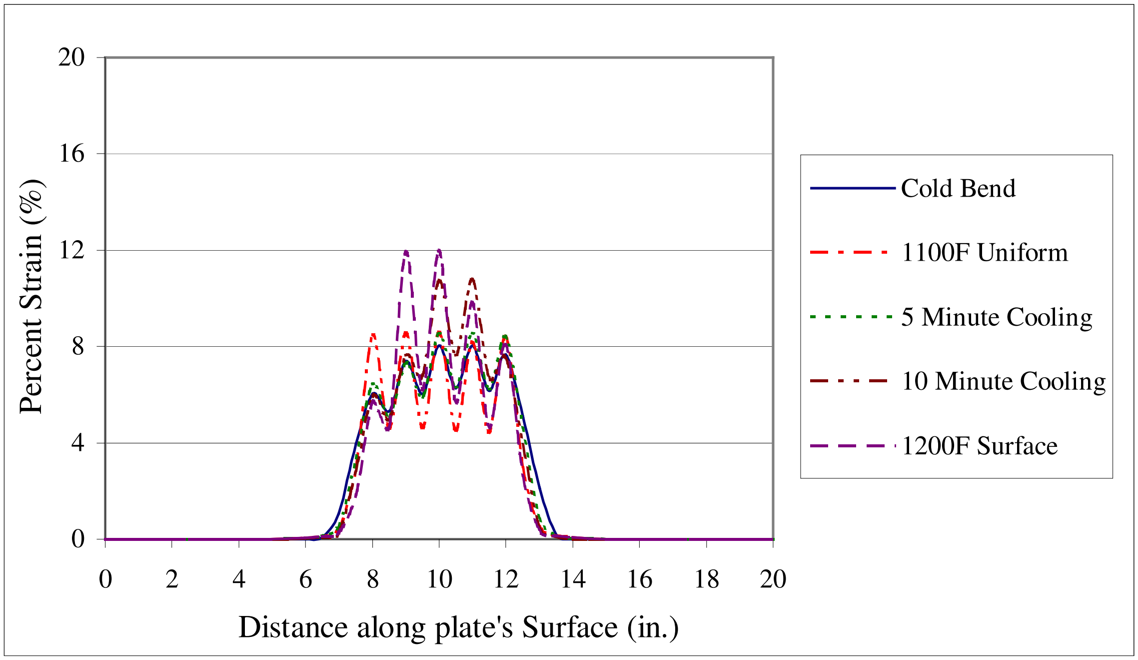


Figure 5-7. Surface Strain 1 inch Plate - 50 ksi

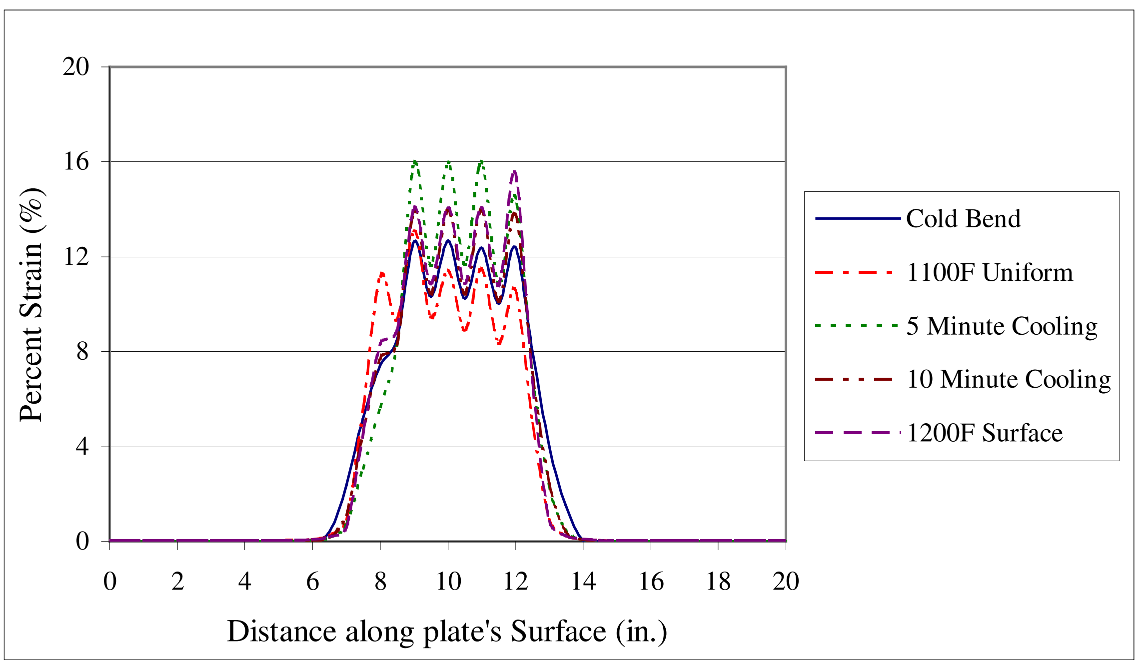


Figure 5-8. Surface Strain 1.5 inch Plate - 50 ksi

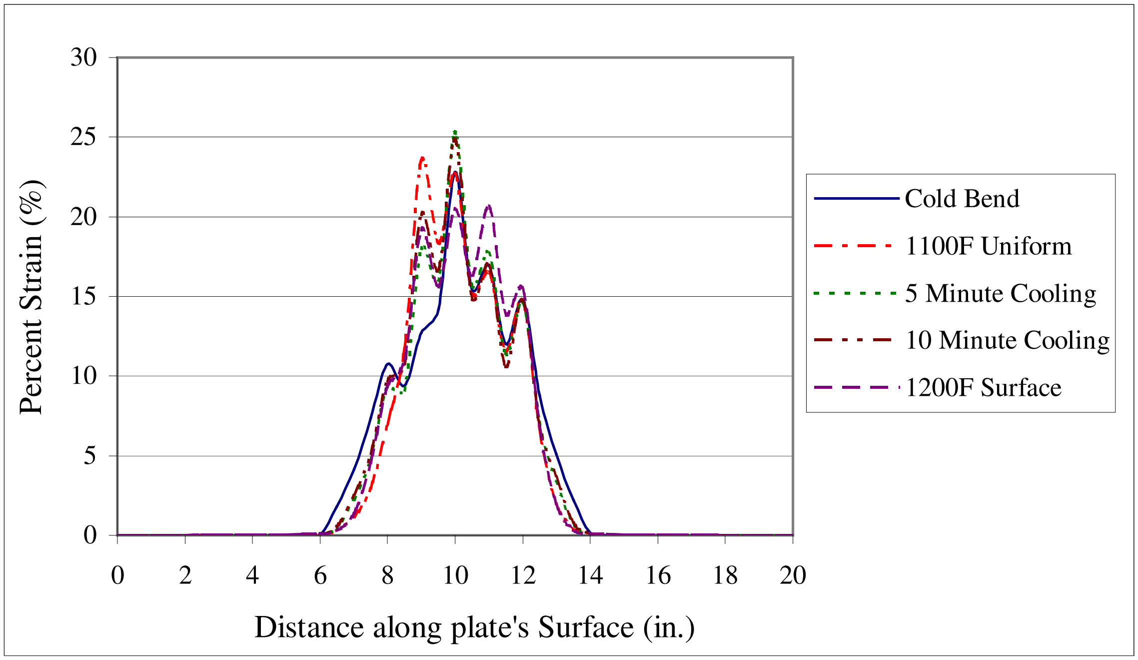


Figure 5-9. Surface Strain 2 inch Plate - 50 ksi

The above figures show to what degree the loading affects the strains along the steel's surface. However, it was determined that strain results would be shown at only one location along the plate's surface in order to get a clearer understanding of how the temperature gradients affect the strains before and after the load passes a location. The location that was selected for observation was the location directly below the load that was applied during load step three. This location was taken because of the fact that five point loads were used in order to obtain the correct bend so there was an equal number of hits before and after the point of observation. In Figure 5-10, very little strain was observed during the first two loadings but there was a significant increase in the strain level when the load was applied directly at the observed location. As the load was removed there was a slight decrease in the strain for all temperatures studied due to the elastic springback as the plate was unloaded. When the next loading occurred one inch from the previous location there was an increase in strain but the strain never reached the magnitude that it was when the load was applied directly at the observed location. Observing the strains occurring in the one and a half inch plate (Figure 5-11), there was an increase in strains as a result of the temperature gradient as a result of the plate cooling for five and ten minutes with the cold bend and 1100^{o}F uniform temperature having approximately the same strain. In Figure 5-10, this same observation can be made with the exception of the one inch plate that was allowed to cool for five minutes. One reason for a one inch plate did not have an increase in strain after five minutes of air-cooling, could be due to the fact that after five minutes of cooling there was only a small temperature gradient present. When the plate size increased to one and a half and two inches, the temperature gradient was more substantial and had a greater influence on the amount of residual strains that would occur. In Figure 5-12, the resulting strains for the two-inch plate follows the same pattern as that of the one and a half inch plate with the only difference between them being the 1200^{o}F torch heating. The strains resulting from the bending of a two-inch plate at 1200^{o}F was less than that of the other temperatures that were studied. The amount of strain occurring at 1200^{o}F is more susceptible to the amount of deflection that will occur at the bend location than would otherwise be encountered at lower temperatures because of the stress-strain curve at 1200^{o}F closely resembling a bilinear curve.

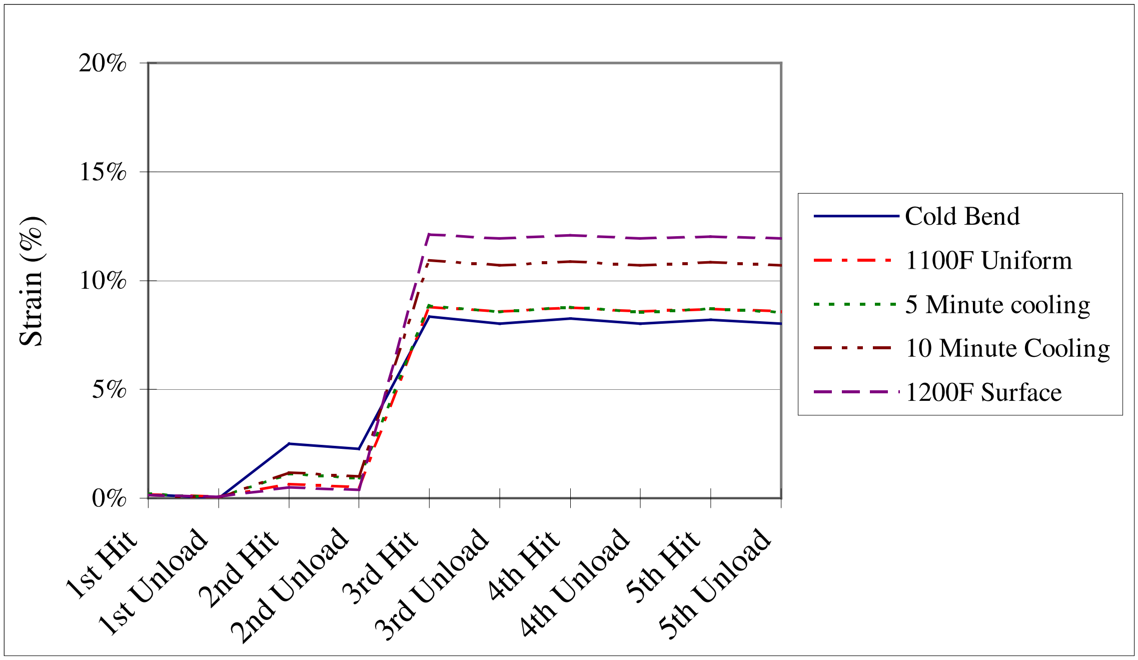


Figure 5-10. Surface Strain at a Point 1 inch Plate - 50 ksi

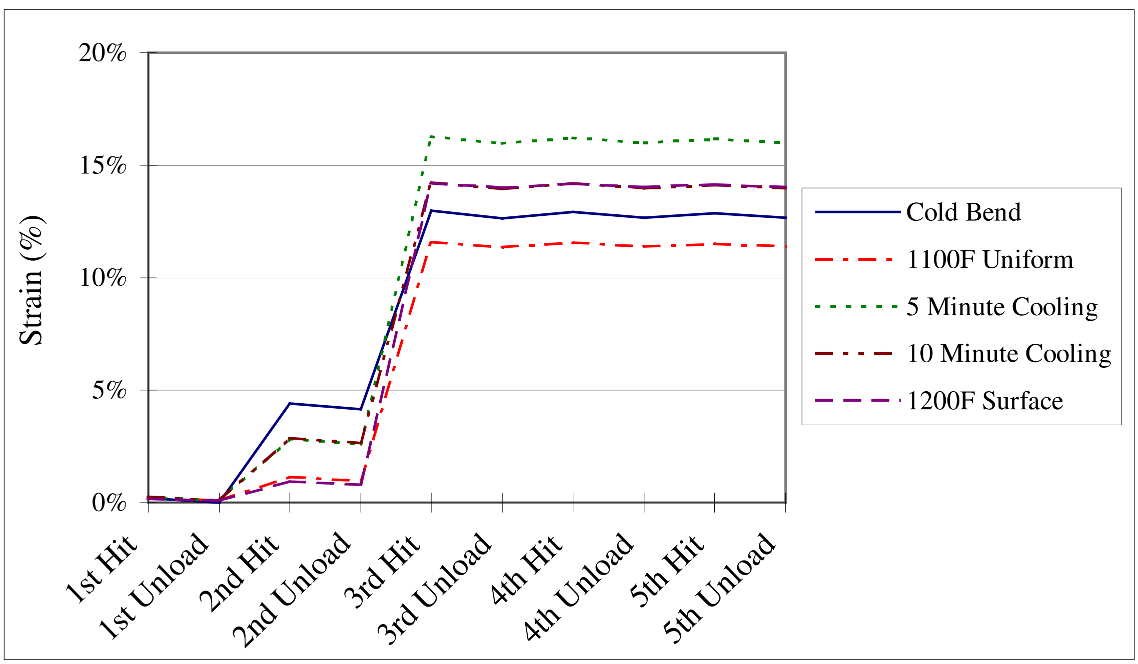


Figure 5-11. Surface Strain at a Point 1.5 inch Plate - 50 ksi

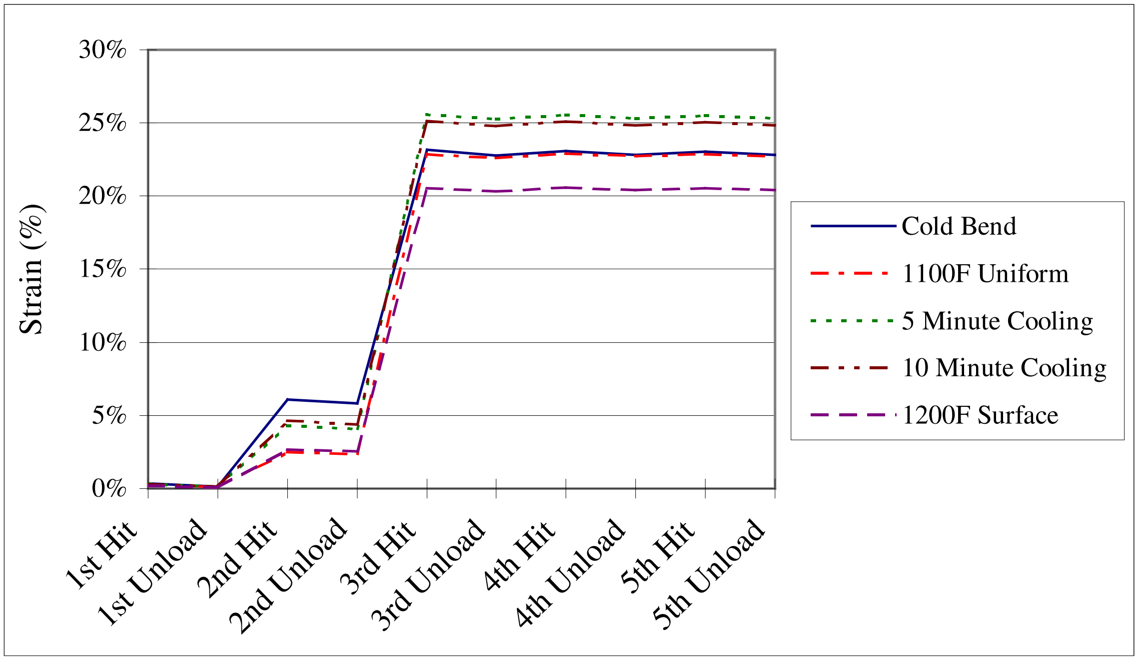


Figure 5-12. Surface Strain at a Point 2 inch Plate - 50 ksi

The ASME (2004) Boiler and Pressure Vessel Code, in section UCS 79, sets a limit on the amount of strain that can occur to 5 percent from the as-rolled condition before heat treatment to stress-relieve has to be applied after the fabrication process is complete. Another restriction that is placed on the fabrication of boiler and pressure vessels is that if the material is formed in the temperature range of 250^{o}F to 900^{o}F the material has to undergo heat treatment after forming. This rule for the temperature during forming was put into place in order to reduce the effects of the temperature gradient and the formation of residual stresses. The temperature limits are also in place to keep the steel out of the blue brittleness range during fabrication. After five and ten minutes of air cooling, all of the plates studied were in this temperature range requiring heat treatment, except for the two-inch thick plate that was air cool for five minutes. To further add to the need for the use of heat treatment after bending is completed, all plates that were studied had strains higher than the 5 percent limit that is set by the ASME (2004) Boiler and Pressure Vessel Code. Some researchers have stated that the 5 percent limit is to conservative for today's clean steel and have proposed a higher limit of 7 percent ((Bala and Malik 1983), (Blondeau et al. 1984)), but even at this elevated limit, all plates studied would still have to undergo heat treatment even without the consideration of the bending temperature that was used during the bending process. Because of this 5 percent strain limit that was placed on the formation of the boiler and pressure vessels, it was decided to investigate the amount of strain that was needed at the time of bending to achieve the final 5 percent strain and to see if the radius could be obtained at this strain limit. In Table 5-2, the initial strains needed to obtain the 5 percent final strain for the various plate thicknesses and grades of steel varied from around 5.3 percent to as high as 5.5 percent. With the ASME Boiler and Pressure Vessel Code strain limits the radius of bend that can occur before heat treatment is required is 10 inches, for a one inch thick plate, over half again the radius that is desired by the bridge fabrication industry. Therefore, by following the ASME (2004) code requirements, heat-treatment would always have to be preformed after the bending process was complete. The same observations can be made for steel having a yield strength of 70 ksi, the graphs for which can be found in the Appendix B.

Table 5-2. Five Percent Strain

Thickness	Yield Stress	Load at Midspan (kips)	Initial Strain (%)	Final Strain (%)
1	50	40.8	5.3	5
1.5	50	86.4	5.4	5.1
2	50	150	5.4	5.1
Thickness	Yield Stress	Load at Midspan (kips)	Initial Strain (%)	Final Strain (%)
1	70	55.9	5.4	5.0
1.5	70	91.5	5.4	5.0
2	70	200	5.5	5.0

5.2.3. Thru-Thickness Stresses

The thru-thickness stress distributions remained relatively the same for the different plate size and the various steel grades studied. Because of this, only the one-inch plate thickness for the 50 ksi steel will be discussed with the remaining results for the other plate thicknesses found in the Appendixes. In Figure 5-13 to Figure 5-16, the graphs refer to various hits. Each of these hits was observed at a single location to determine what effect multiple bend points in the fabrication of bent flange plates would have. The location thru the plate's thickness that was chosen as the point of reference was the location directly below the load application for the third bend point. The first hit that is shown in the figures occurs at a point two inches from the point of observation while the next hit progresses one inch towards the point, and after the third hit the next two hits continue passed the point of observation at one inch intervals.

When looking at the results that were graphed in Figure 5-13 thru Figure 5-16, the highest stresses occurred during cold bending while the lowest occurred when the plate's surface was heated to 1200°F. This result can be explained by the simple fact that the magnitude of the stress-strain curve for steel is much higher at low temperatures than at high temperatures. The graphs also indicate that the highest stresses thru the plate's thickness occur when the load is applied directly above the location under consideration with the stress decreasing after the load passes.

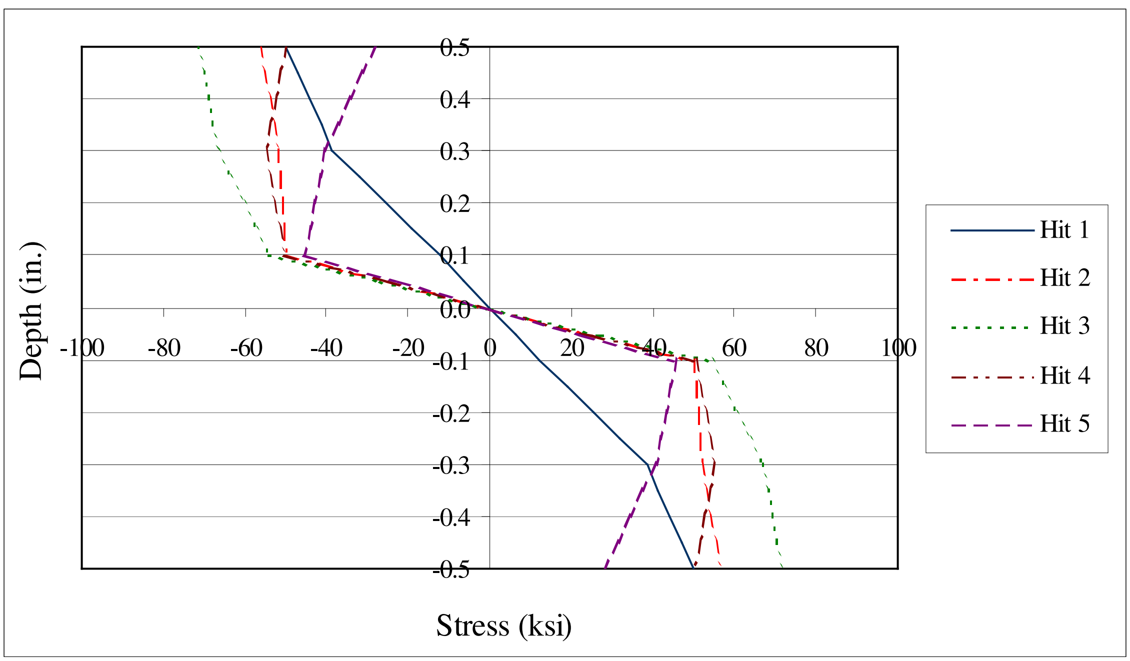


Figure 5-13. Thru-Thickness Stress Cold Bend - 50 ksi

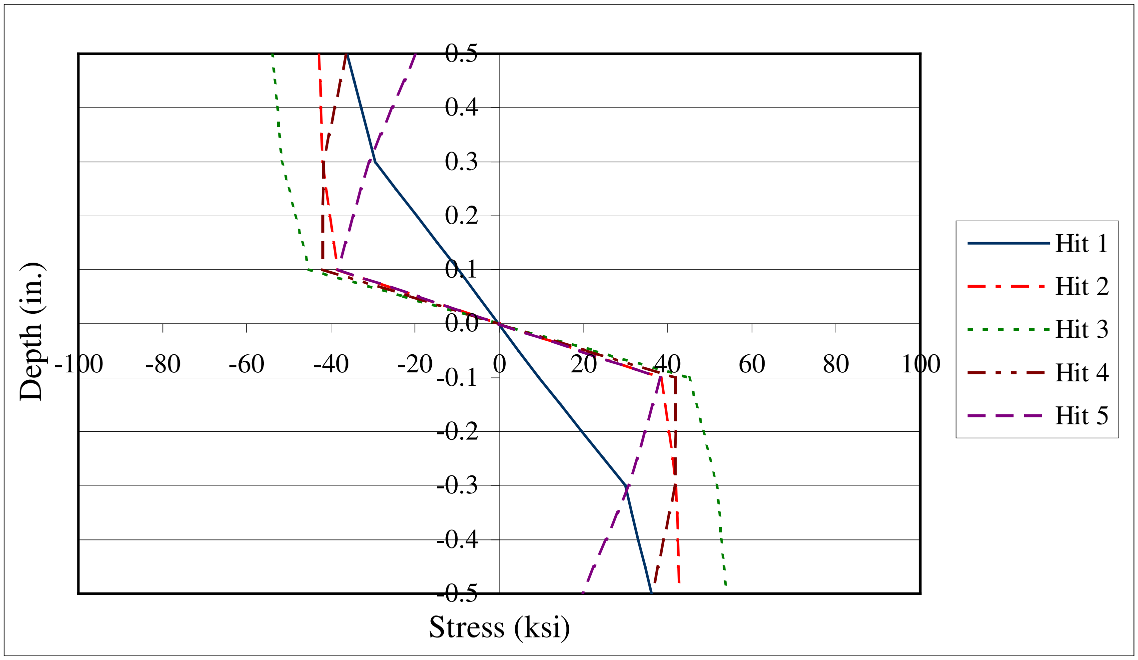


Figure 5-14. Thru-Thickness Stress 10 Minute Cooling - 50 ksi

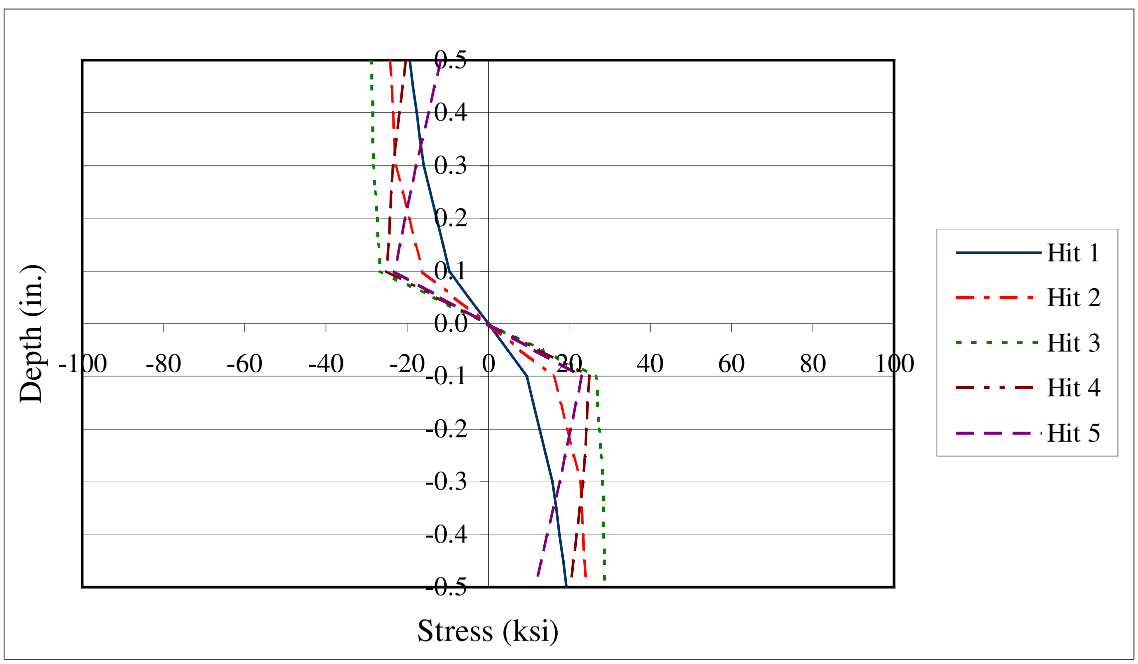


Figure 5-15. Thru-Thickness Stress 1100°F Uniform Temperature - 50 ksi

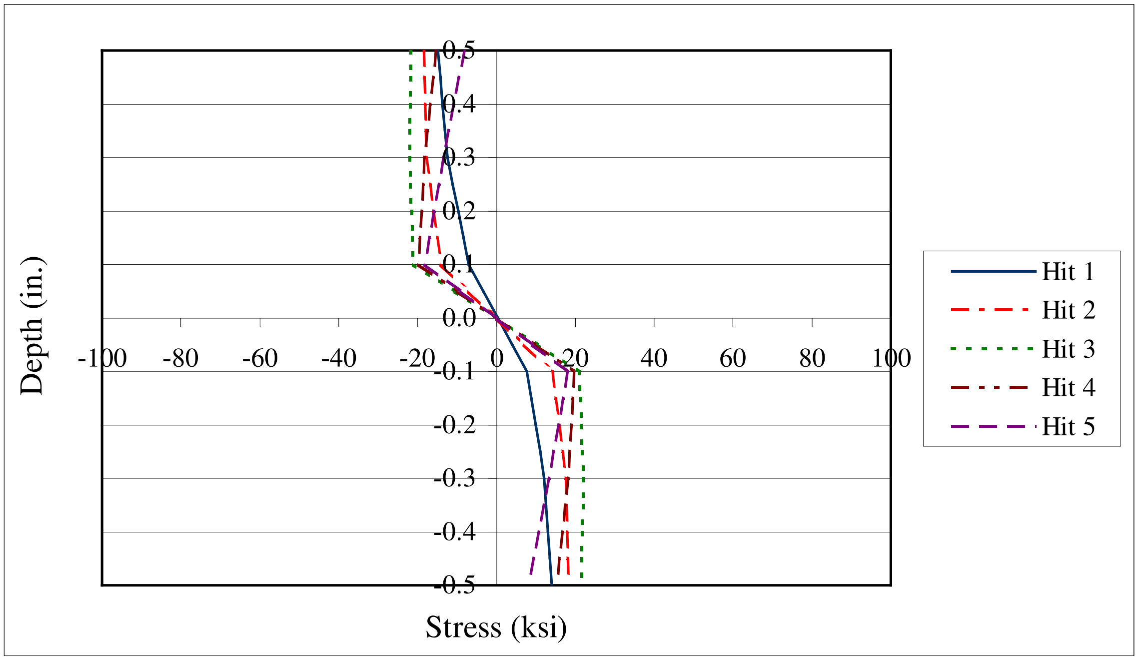


Figure 5-16. Thru-Thickness Stress 1200^{o}F Surface Temperature - 50 ksi

As the load came closer, the fibers yielded within 1/10 of an inch from the neutral axis. One of the drawbacks from using the finite element mesh of 0.2 inch squares is that the material can only yield to a node closest to the neutral axis, which for a Quad 8 Node 82 at that mesh size is 1/10 of an inch. This restriction is brought about by one of the principles in mechanics of materials that the plate will always have some portion around the neutral axis behaving elastically (Boresi and Schmidt 2003). The plate that was allowed to air-cool for ten minutes after obtaining an 1100^{o}F uniform temperature underwent the bending process the stresses are shown, Figure 5-14, to resemble that of cold bending. Comparing the stresses between the two, the difference was only 10.6 ksi to 17.5 ksi, 0.15 inches from the neutral axis and extreme fiber respectively; this difference in stress will later be shown to give a very small reduction in the residual stress thru the plate's thickness. When the plate was bent at both a uniform temperature of 1100^{o}F and with a 1200^{o}F surface temperature, the temperature in the plate caused a large reduction in the plates thru-thickness stresses. The behavior of the plate bent at 1100^{o}F, shown in Figure 5-15, continues the pattern discussed but with the increase in the plate's temperature the stress curve at hit 3 holds a constant stress thru the plate's thickness. The reason for this is the stress-strain curve, Figure 5-1, resembling a bilinear curve, and the benefit to this is that, as the load is increased, the strain in the material will increase while the stress remains constant. Therefore, the residual stresses are constant after a certain level of stress is reached. For a plate that was bent after torch heating was used (Figure 5-16) the stresses were further reduced compared to what the uniformly heated plate experienced. After the load passes, a certain location the stress in the plate will no longer be effected by the load being applied. This was seen after the load had progressed two inches past the point of observation, shown as hit five of Figure 5-16.

5.2.4. Thru-Thickness Residual Stresses

The magnitude of stress through the plate's thickness, as discussed in Section 5.2.3, indicates whether or not residual stresses will occur in the plate after the plate is unloaded. If the stress goes past the yield point of the material and into the plastic region of the stress-strain curve, a residual stress will remain after unloading. The amount of stress remaining is directly related to the magnitude of strain that developed during the loading process. When considering the residual stress distribution through a plate's thickness, one area of consideration was the amount of tensile residual stress on the inside surface of the plate bend for it could cause cracking and stress corrosion (Weng and White 1990a).

After each loading phase, the plate was allowed to unload to simulate using a brake press to fabricate the bent flange plate. In Figure 5-17 thru Figure 5-20, the location where the thru-thickness residual stresses were observed was at the same location that was used in the previous section; under the location were the third loading occurred. Following this procedure, it was observed that in all of the plate thicknesses studied, the residual stresses are at their highest levels at the applied load location. And, as the load progressed past the previously loaded location the residual stresses remain relatively constant.

When comparing the residual stresses caused by bending a plate at room temperature (Figure 5-17) to that of the other temperatures studied, the plate undergoes the largest magnitude of residual stress. On the inside surface of the bent plate, there was found to be 23 ksi tensile residual stress present. This extreme fiber residual stress is approximately, one-half of the yield strength of the material that was studied. This indicates that a large amount of plastic deformation occurred in the plate at the time of bending. As the residual stresses approach the neutral axis, the stresses change from tensile to compression with the maximum residual stress occurring 1/10 of an inch from the neutral axis. The maximum residual stress at that location was found to be 35 ksi. When looking at the plate after it is allowed to cool from an 1100^{o}F uniform temperature and then bent (Figure 5-18) the residual stresses were only slightly different than that of the cold bending results. The tensile residual stress on the plates inside surface at 18.7 ksi after the bending process was complete. The residual stress occurring near the plate's neutral axis also decreases slightly to 30 ksi. There was only a difference of around 5 ksi from the plate that was bent at room temperature to the plate that was bent after it was heated to 1100^{o}F and allowed to air cool for 10 minutes. The plate that was allowed to air cool for 5 minutes from a 1100^{o}F uniform temperature and then under went the bending process was also found to have the same relatively small decrease in the residual thru-thickness stress as that of the plate that was cooled for 10 minutes.

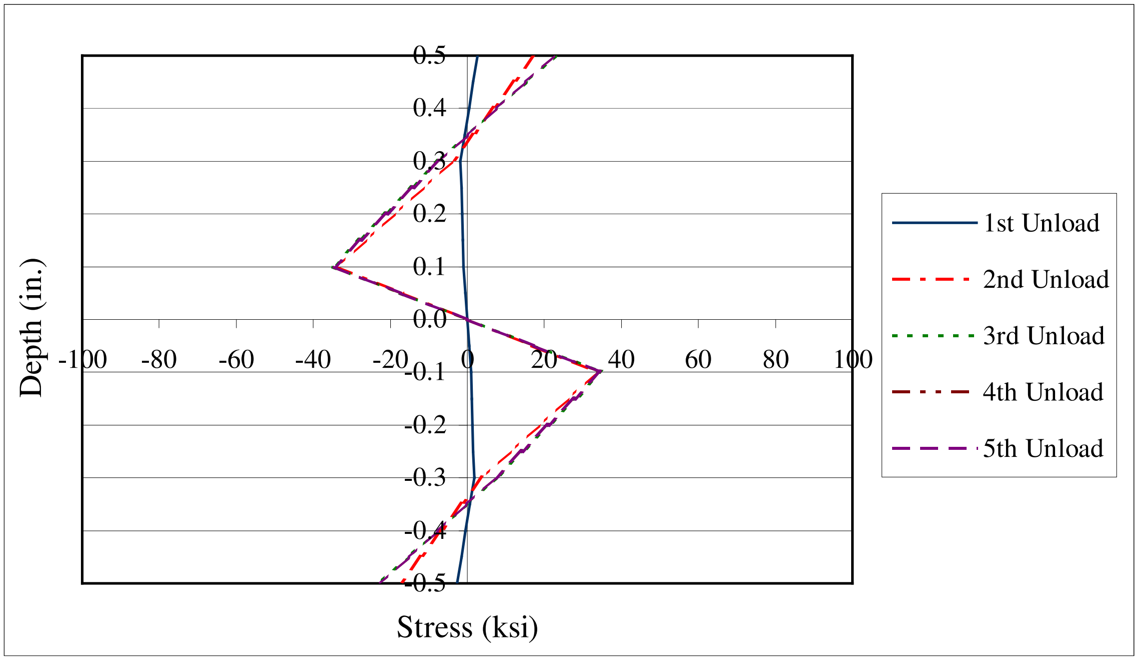


Figure 5-17. Thru-Thickness Residual Stress Cold Bend - 50 ksi

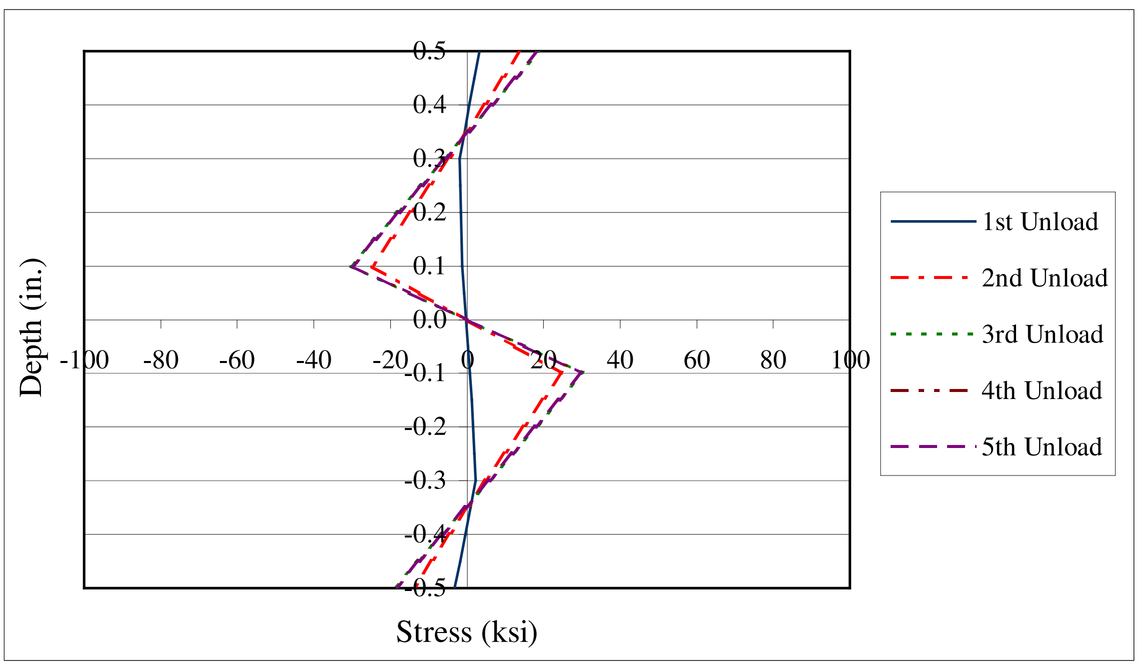


Figure 5-18. Thru-Thickness Residual Stress 10 Minute Cooling - 50 ksi

When the plate was heated to a uniform temperature of 1100^{o}F (Figure 5-19) and immediately bent so that no thermal convection occurred, there was a significant decrease in the residual stress through the plate's thickness compared to both the plate that was bent at room temperature and the plates that were allowed to air cool for five and ten minutes. This decrease in residual stress was a result of the decrease in the steel's stress-strain curve, for there is a significant decrease in the amount of stress that the plate can undergo during the bending process. This results in a decrease in the residual stress that develops upon unloading. The tensile residual stresses that developed when the plate was heated to 1100^{o}F at the extreme fibers was 11 ksi, which was only about 1/2 of the residual stress occurring after bending the plate at room temperature. The residual stress near to the neutral axis was 18 ksi, which was also around a 50 percent decrease. When bending the plate after a torch was used to heat the plate's surface to a temperature of 1200^{o}F, the residual stress decreased even more than when the plate was bent at a uniform temperature of 1100^{o}F. The tensile residual stress at the plate's extreme fiber was 8.5 ksi, Figure 5-20, and the residual stress found next to the plate's neutral axis was 14.5 ksi.

There was a significant decrease in residual stresses when the plate was bent at both an 1100^{o}F uniform temperature and after the plate was heated using a torch to a surface temperature of 1200^{o}F compared to the residual stresses after cold bending. When the plate that was heated to 1100^{o}F was allowed to cool for ten minutes, there was a significant rise in the amount of residual stress that occurred after the bending process.

This rise in residual stress was brought on by the increase in the steel's stress-strain curve.

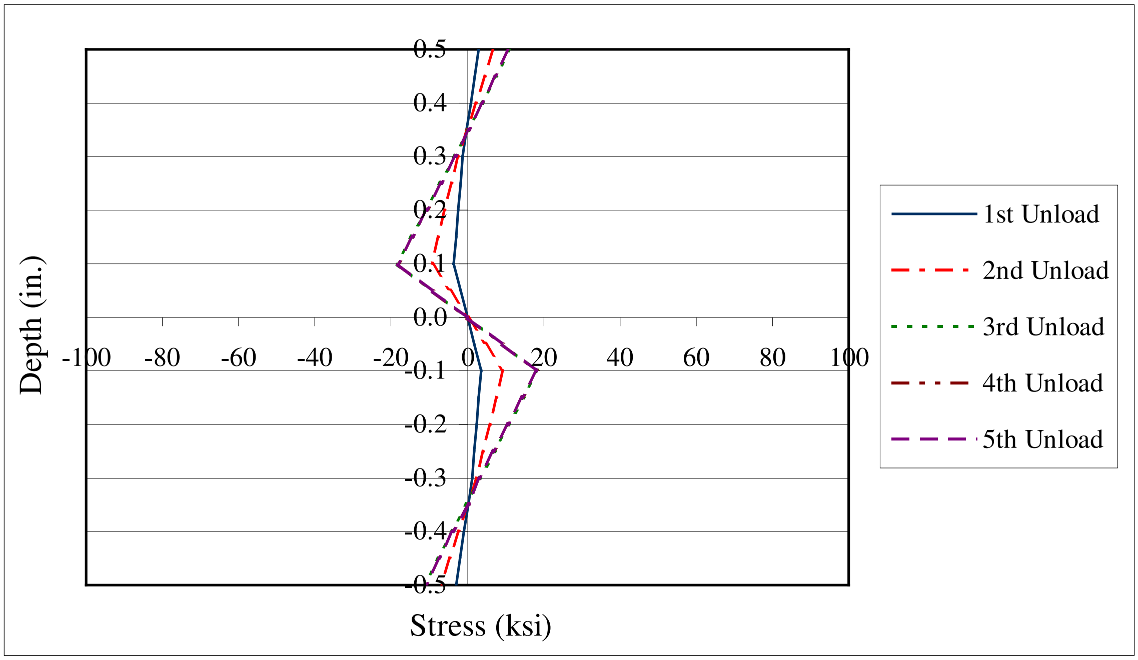


Figure 5-19. Thru-Thickness Residual Stress 1100°F Uniform - 50 ksi

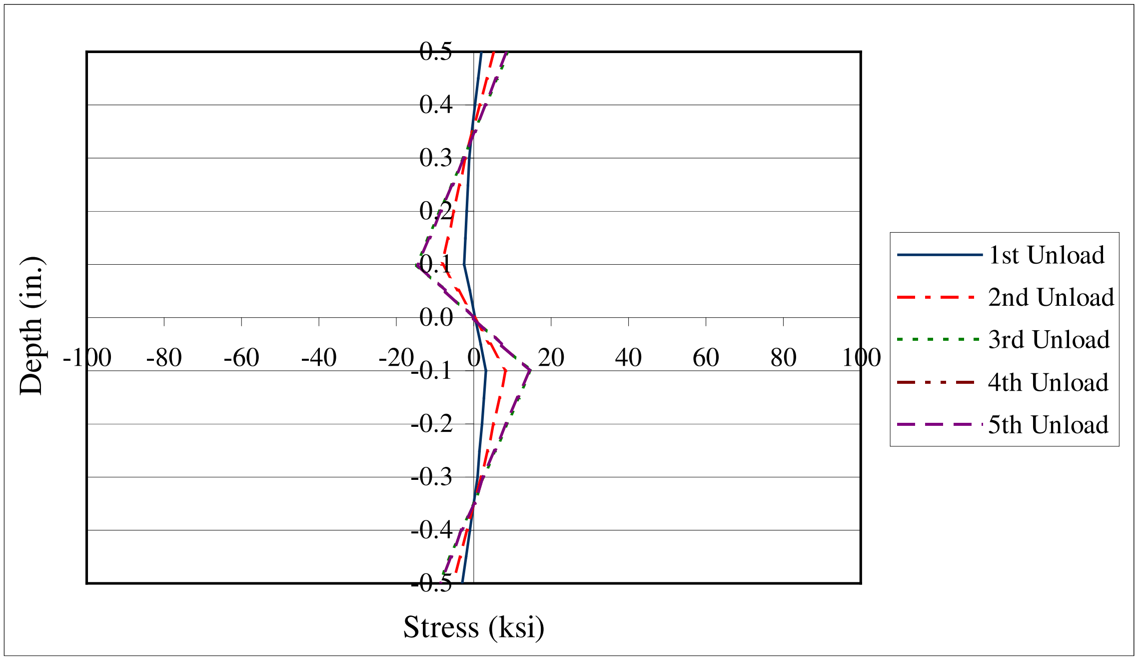


Figure 5-20. Thru-Thickness Residual Stress 1200^{o}F Surface Temperature - 50 ksi

6. SUMMARY AND CONCLUSION

6.1. Summary

Steel fabricators for TxDOT have occasionally encountered cracking of the flange plates during fabrication of dapped girders. The cracks develop during the bending process, particularly when heat is used to assist the process. Because of the excessive strains (10 to 16 percent) resulting from the bending process, the present study used the Finite Element Method to investigate the process. Plates having a thickness of one, one and a half, and two inches were simulated to undergo brake press bending.

In order to get a better understanding of what heating and fabrication processes the fabricators are to follow, several industry standards were look at, including the ASME (2004) “Boiler and Pressure Vessel Code”, AASHTO/NSBA (2002) “Steel Bridge Fabrication Guide Specification”, and the FHWA (1998) “Heat Straightening Repairs of Damaged Steel Bridges.” The maximum temperature fabricators are allowed to heat the steel to is 1200^{o}F. Therefore, the present study investigated the bending process at room temperature, a uniform temperature of 1100^{o}F, both five and ten minutes of air-cooling of a plate after it reached a uniform temperature of 1100^{o}F, and the use of a torch to heat the plate’s surface to 1200^{o}F. These temperatures were simulated in order to investigate how the application of heat and subsequent cooling would affect the stress and strain distributions during the fabrication process. The 90-degree, six-inch radius detail was studied since some manufacturers are experiencing cracking during the fabrication process.

Since there was a lack in experimental data for determining the stress-strain-temperature curves of grade 50 and 70 structural steels, it was necessary to simulate the change in the stress-strain behavior as a function of temperature. Several studies have been done in this field and each gave various means of depicting the stress-strain curves through the use of equations, but it was determined the equation provided by Poh (2001) was the most accurate for the types of steel used in the fabrication of steel highway girders.

It was also determined that in order to accurately simulate temperature gradients during the bending process, two separate finite element models were used. One modeled the application of heat (thermal model) and the other model was used to study the bending process (structural model). The thermal model simulated two different heating methods. One method was the use of a furnace to heat the plate to a uniform temperature and then allowing the plate to air-cool once it reached a uniform temperature of 1100^{o}F, and the other thermal process was the heating of the flange plate by means of a torch. Each of the resulting temperature gradients was then imported into the structural model to investigate the effects of heat on the bending process. Once a 90-degree six-inch radius was obtained, the resulting stresses and strains were plotted to observe what effects the temperature gradient had on the thru-thickness stresses and strains.

Because the Finite Element Method was used, it was necessary to compare the results to other analysis methods in order to ensure that the results being generated were reasonable. To do this, two different analytical methods for calculating the strains of a six-inch radius were compared to the finite element results. The analytical equations used for comparing the strains included the equations proposed by the ASME (2004) Boiler and Pressure Vessel Code and the equations cited by Weng and White (1990a). After comparing the results given by ANSYS to the analytical results, it was determined that the computer generated strains were within reason and with a fair amount of certainty could be considered an accurate representation of the bending process.

6.2. Conclusions

Research reported herein was conducted to obtain a better understanding of how the heating to elevated temperatures would affect the residual stress and strain distributions that result from the bending of the flange plate. As a result of this study, several conclusions can be made about the different methods of heating and whether or not the resulting temperature gradients could be a significant factor in causing the flange cracking. The conclusions drawn from this in-depth study are as follows.

6.2.1. Thermal Conclusion

- The temperature gradient thru the plate's thickness increases as the plate's thickness increases.
- As the thickness of the plate increases so does the time it takes the plate to cool down to its original temperature.

- The thermal expansion brought on by torch heating causes compression stresses to form on the plate's extreme fibers. When the plate is then air-cooling from a uniform temperature tensile stresses form on the plate's surface.

6.2.2. Structural Conclusions

- Observing the plate's strain at a point along the plate's surface during the bending process, the plates that had temperature gradients present during bending had higher strains than plates that where bent at a uniform temperature.
- In the region of ten percent of steel's uniaxial stress-strain curve necking can occur. This necking during a uniaxial test results in cracking when the same strain level is observed during the plate bending process. As a result of this both the one and a half and two-inch plates exceed this strain level and can, therefore, develop cracks as a result of excessive strains.
- The six-inch radius bend, for all the plate thicknesses tested, exceeded the strain limits of the ASME (2004) Boiler and Pressure Vessel Code.
- After the plate that was heated to a uniform temperature of 1100^{o}F and then allowed to air-cool for five minutes, the residual stresses after bending the plate to a six-inch radius would be significantly increased from what would have been experienced if the plate were bent at a uniform temperature of 1100^{o}F. This same result was observed when the plate was air-cooled for ten minutes and bent.

The stresses formed due to the cooling are of the same magnitude as the stresses formed from cold bending.

- When the plate was bent after torch heating the residual stresses were lower than any other temperature tested. With the next lowest surface residual stress occurring when the plate was bent at a uniform temperature of 1100^{o}F.
- The effected region caused by the bending process was two times the plate's thickness.
- The addition of heat in the fabrication process is beneficial as long as there are no temperature gradients present at the time of bending. When temperature gradients are present there is an increased likelihood that cracking of the flange plate can occur.

6.3. Further Research

To further expand the conclusions gathered through the current study, additional areas of the plate bending fabrication process should be considered. These areas include:

- Determining if the rate at which the plate is loaded during the fabrication process would increase the plate's risk of developing cracking. Some research conducted by others has suggested that this might play a role in the plate's susceptibility to cracking.

- Determine if the use of dry compressed air after completion of the bending process to cool the plate down would increase the residual stress level than would otherwise occur by natural convection.
- Develop an industry standard for the severity of the bends and at what temperature the plates should be fabricated at in order to not have the risk of developing cracking in the girder's flange plate.

REFERENCES

AASHTO/NSBA. (2002). "Steel Bridge Fabrication Guide Specification." *AASHTO/NSBA Steel Bridge Collaboration S 2.1-2002*, <http://www.steelbridge.org/standards.htm> (Nov. 18, 2004).

ASME. (2004). *Boiler & Pressure Vessel Code*. American Society of Mechanical Engineers, New York.

Avent, R. R. (1989). "Heat-straightening prototype damaged bridge girders." *J. Struct. Engrg*., ASCE, 115(7), 1631-1649.

Avent, R. R. (1992). "Designing heat-straightening repairs." *1992 National Steel Construction Conference Proceedings*, American Institute for Steel Construction, Las Vegas, N.V. 2.1-2.23.

Bala, S. R., and Malik, L. (1983). "Roll forming to higher strain levels successful." *Welding and Metal Fabrication*, 51(2), 100-108.

Blondeau, R., Boulisset, R., Ramon, J.L., Kaplan, D., Roesch, L. (1984). "Cold forming and welding behaviors of heavy plate steels for pressure vessel applications." *5th International Conference on Pressure Vessel Technology, Volume 2: Materials and Manufacturing*, ASME, San Francisco, C.A., 1257-1289.

Boresi, A. P., and Schmidt, R. J. (2003). *Advanced Mechanics of Materials*, 6th Ed., John Wiley and Sons, New York.

Cooke, G. M. E. (1988). "An introduction to the mechanical properties of structural steel at elevated temperatures." *Fire Safety J*., 13, 45-54.

FHWA. (1998). *Heat Straightening Repairs of Damaged Steel Bridges*. Federal Highway Administration, Washington D.C.

Harmathy, T.Z. and Stanzak, W. W. (1970). “Elevated-temperature tensile and creep properties of some structural and prestressing steels.” *Fire Test Performance, ASTM STP 464*, American Society for Testing and Materials, Ottawa, Canada, 186-208.

Kervick, R. J., and Springborn, R. K. (1966). *Cold Bending and Forming Tube and Other Sections*, American Society of Tool and Manufacturing Engineers, Dearbor, M.I.

Kirby, B. R., and Preston, R. R. (1988). “High temperature properties of hot-rolled, structural steels for use in fire engineering design studies.” *Fire Safety J*., 13, 27-37.

Lie, T. T. (1992). *Structural Fire Protection*, ASCE Manuals and Reports on Engineering Practice No. 78, 224-225.

Poh, K. W. (2001). “Stress-strain-temperature relationship for structural steel.” *J. Mater. Civil Engrg*., ASCE, 13(5), 371-379.

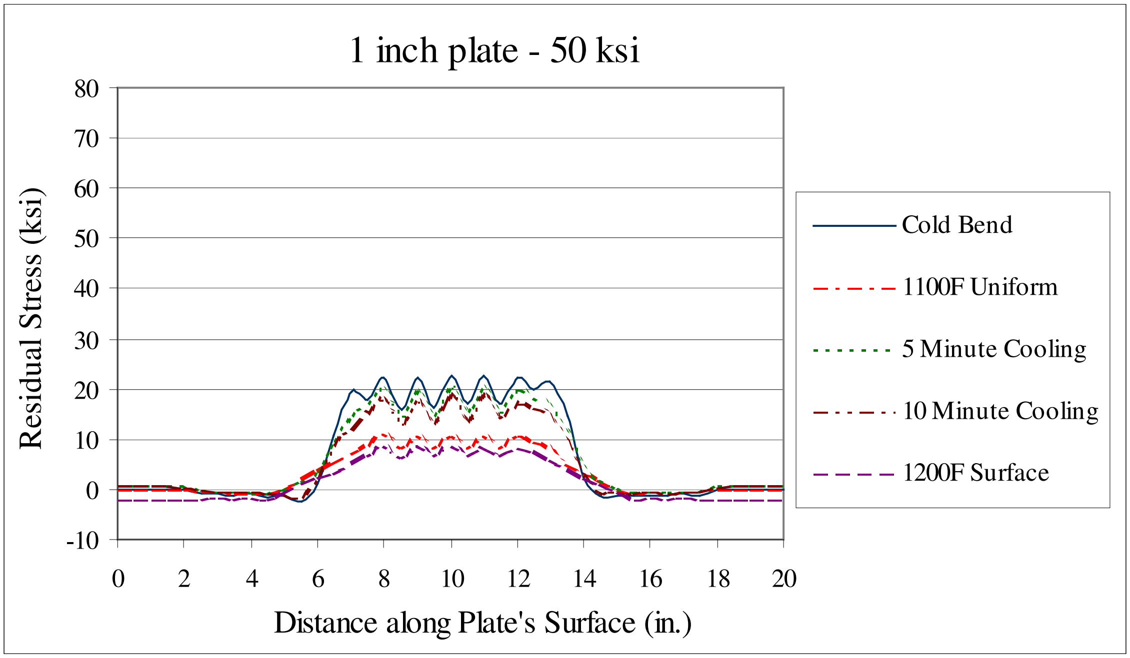
TXDOT (2004). “2004 English Specifications Book Item 784.” Texas Department of Transportation, <www.dot.state.tx.us/business/specifications.htm> (Nov. 18, 2004).

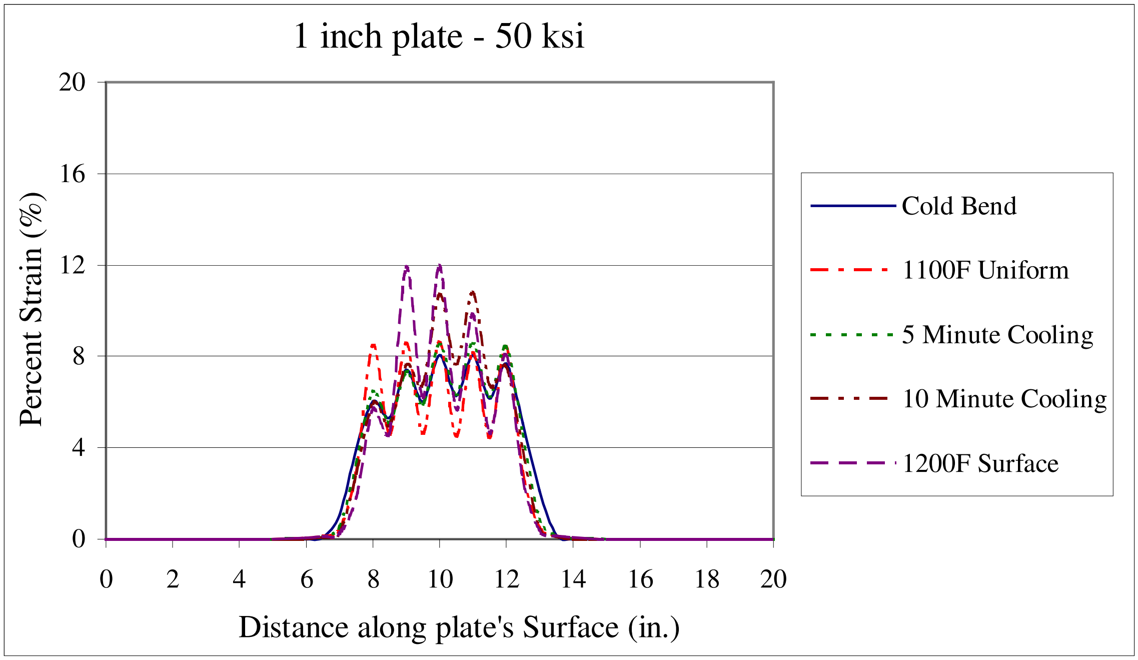
Weng, C. C., White, R. N. (1990a). “Residual stresses in cold-bent thick steel plates.” *J. Struct. Engrg*., ASCE, 116(1), 24-39.

Weng, C. C., White, R. N. (1990b). “Cold-bending of thick high-strength steel plates.” *J. Struct. Engrg*., ASCE, 116(1), 40-53.

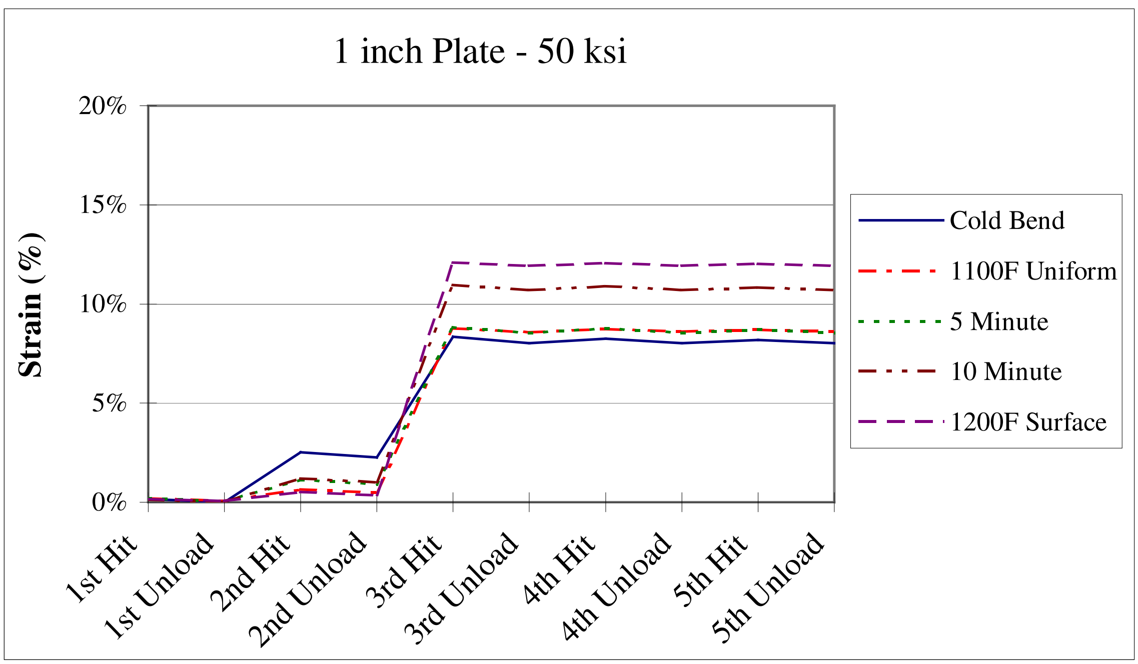
APPENDIX A

GRADE 50 STRESS AND STRAIN DATA

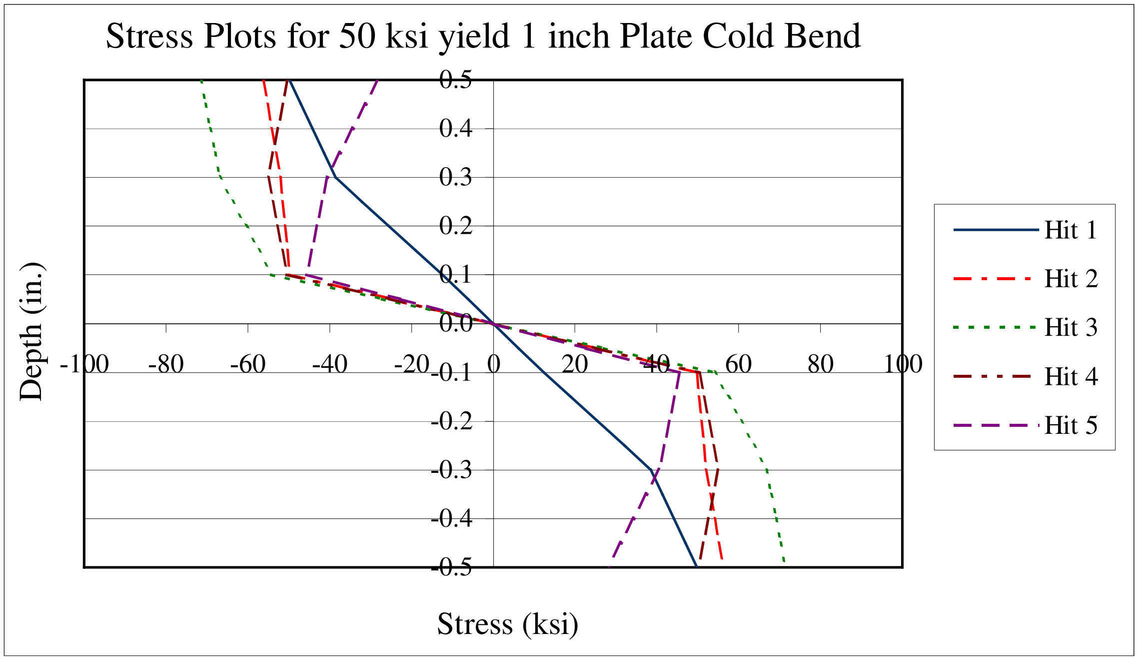


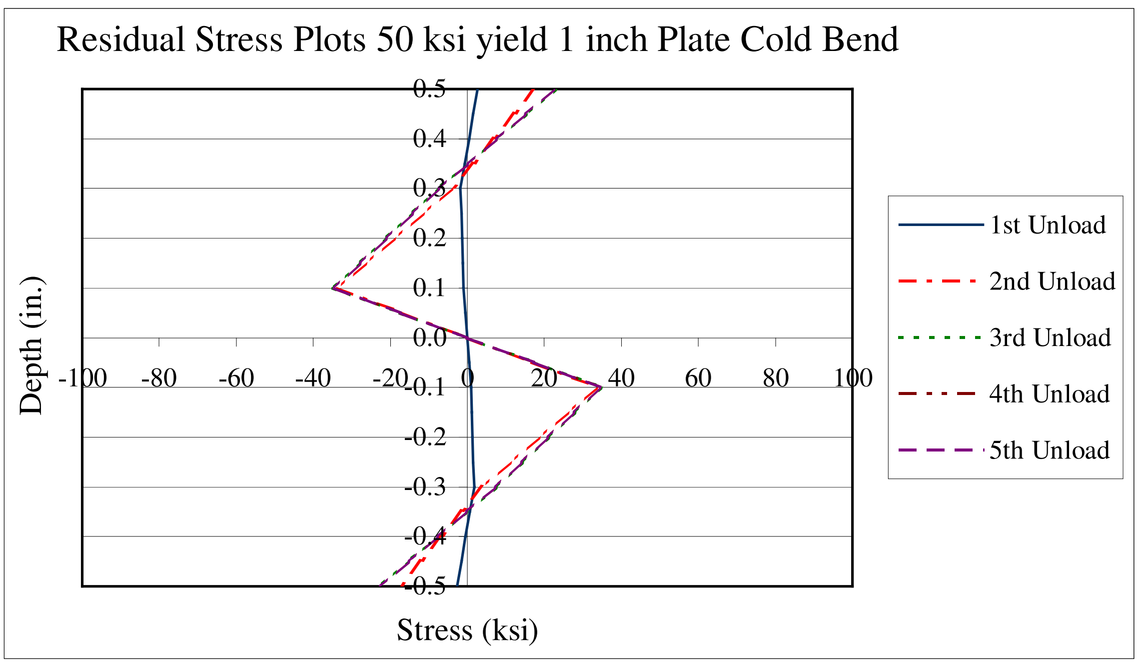


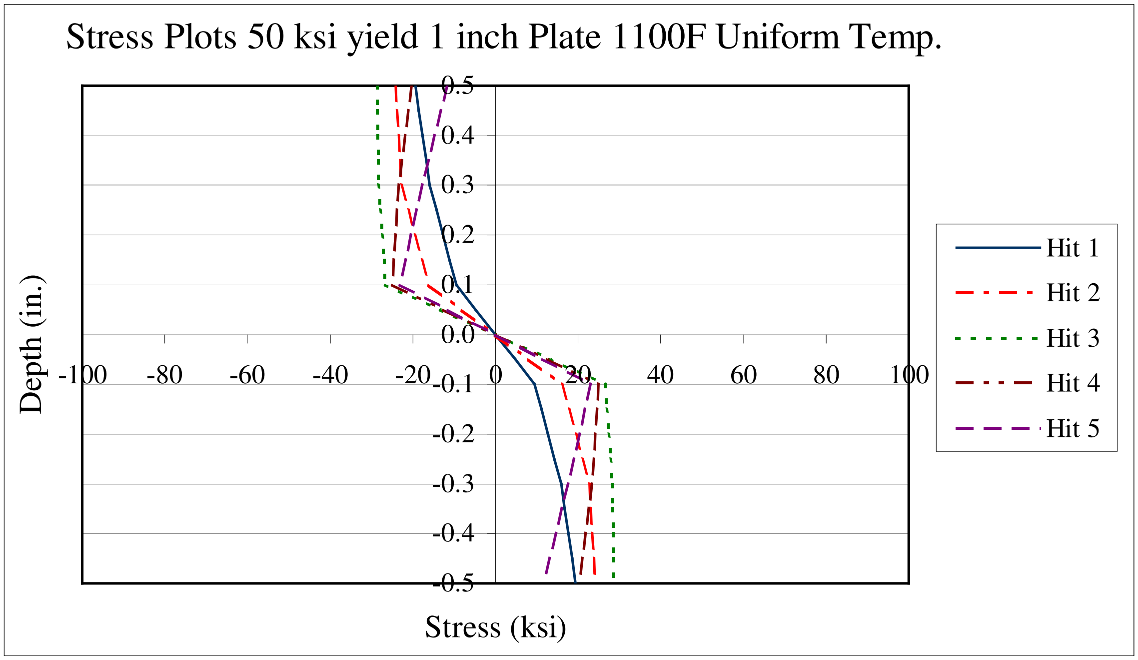
1 inch plate - 50 ksi
Percent Strain (%)
Distance along plate's Surface (in.)
0
4
8
12
16
20
0
2
4
6
8
10
12
14
16
18
20
Cold Bend
1100F Uniform
5 Minute Cooling
10 Minute Cooling
1200F Surface

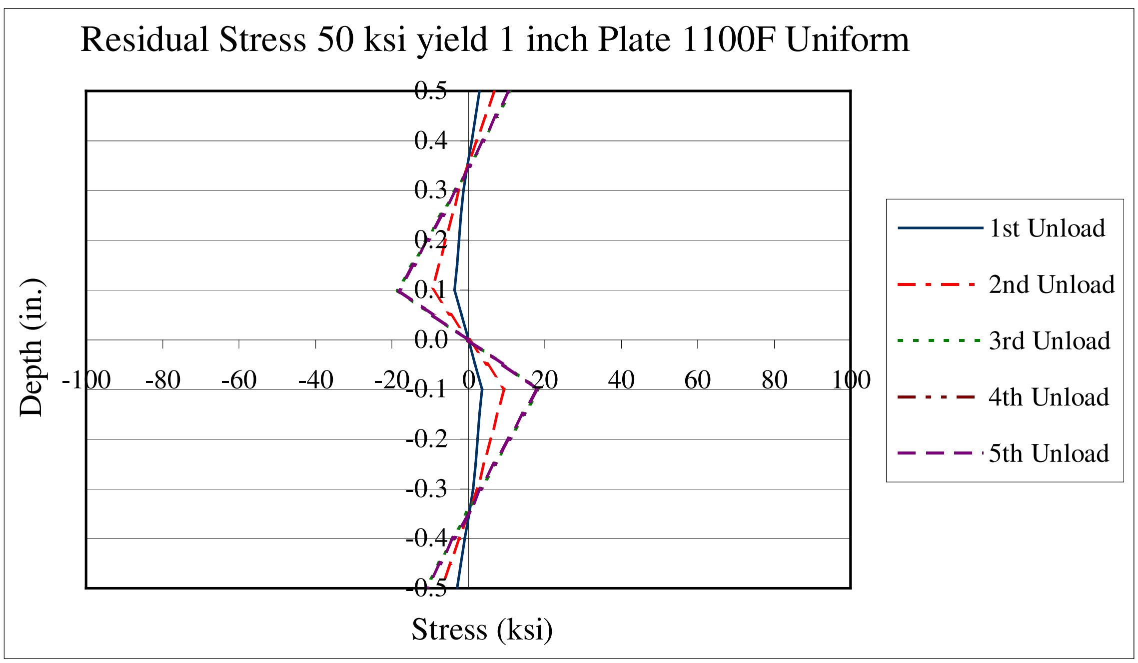


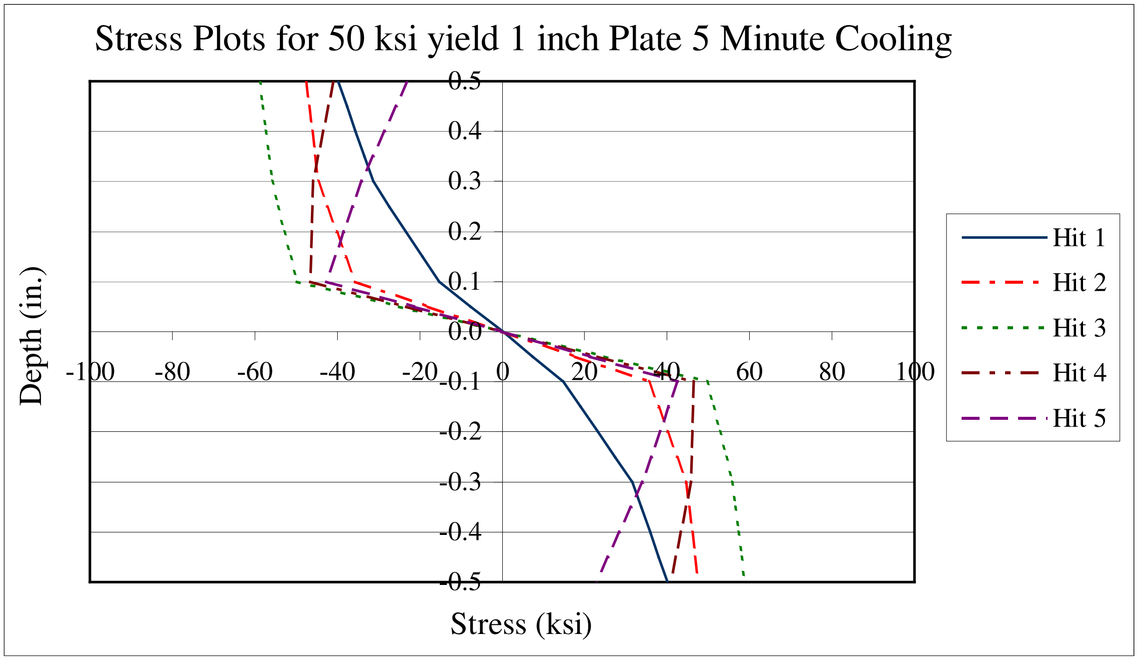
1 inch Plate - 50 ksi
Strain (%)
0%
5%
10%
15%
20%
1st Hit
1st Unload
2nd Hit
2nd Unload
3rd Hit
3rd Unload
4th Hit
4th Unload
5th Hit
5th Unload
Cold Bend
1100F Uniform
5 Minute
10 Minute
1200F Surface

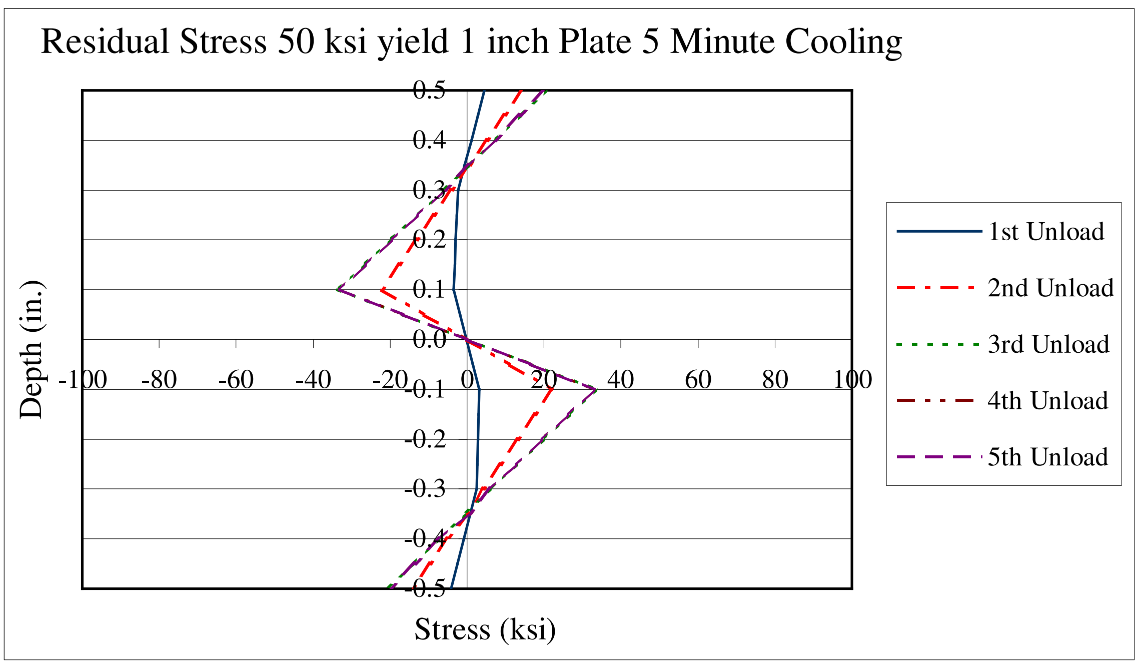

Stress Plots for 50 ksi yield 1 inch Plate Cold Bend
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

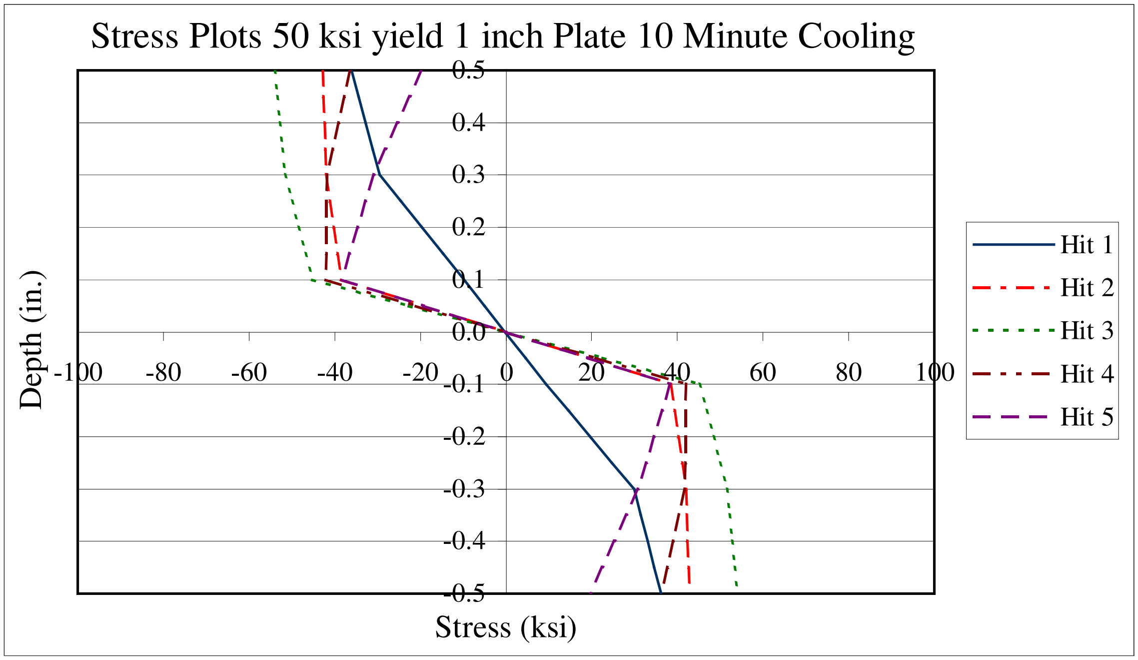

Residual Stress Plots 50 ksi yield 1 inch Plate Cold Bend
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

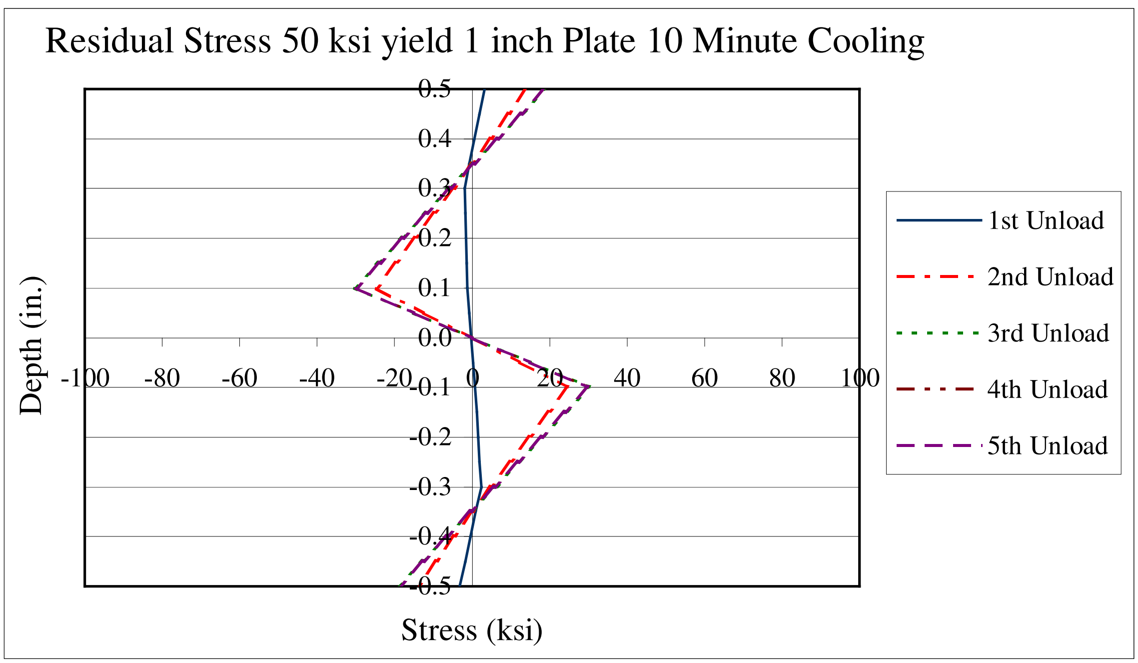

Stress Plots 50 ksi yield 1 inch Plate 1100F Uniform Temp.
Depth (in.)
Stress (ksi)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-100
-80
-60
-40
-20
0
20
40
60
80
100
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

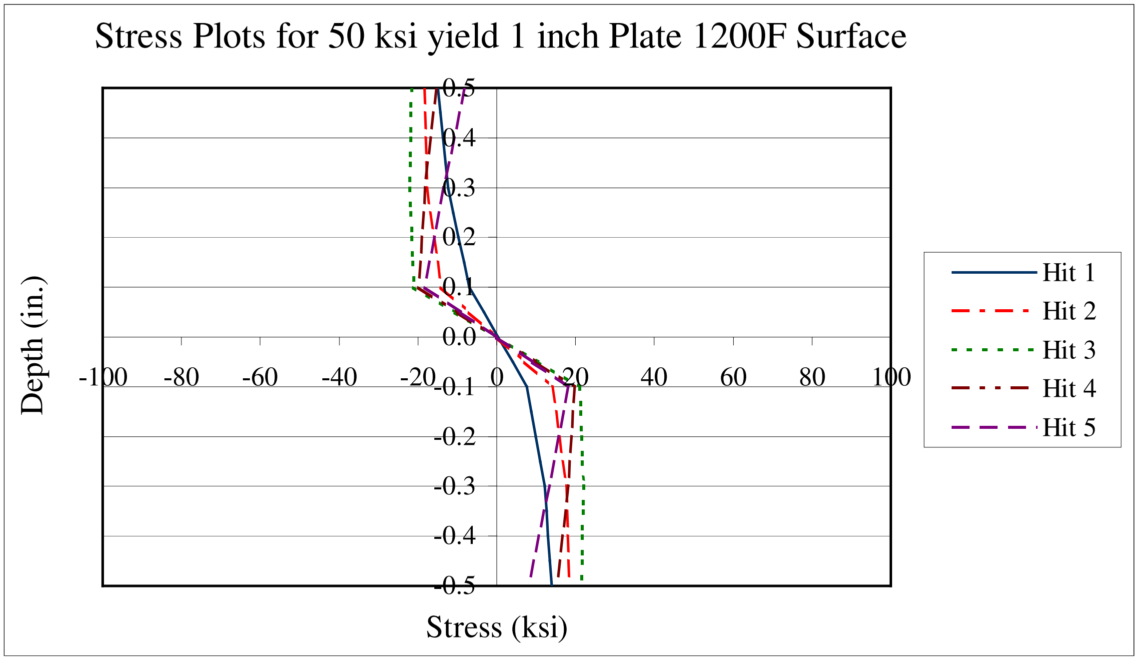

Residual Stress 50 ksi yield 1 inch Plate 1100F Uniform
Depth (in.)
Stress (ksi)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-100
-80
-60
-40
-20
0
20
40
60
80
100
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

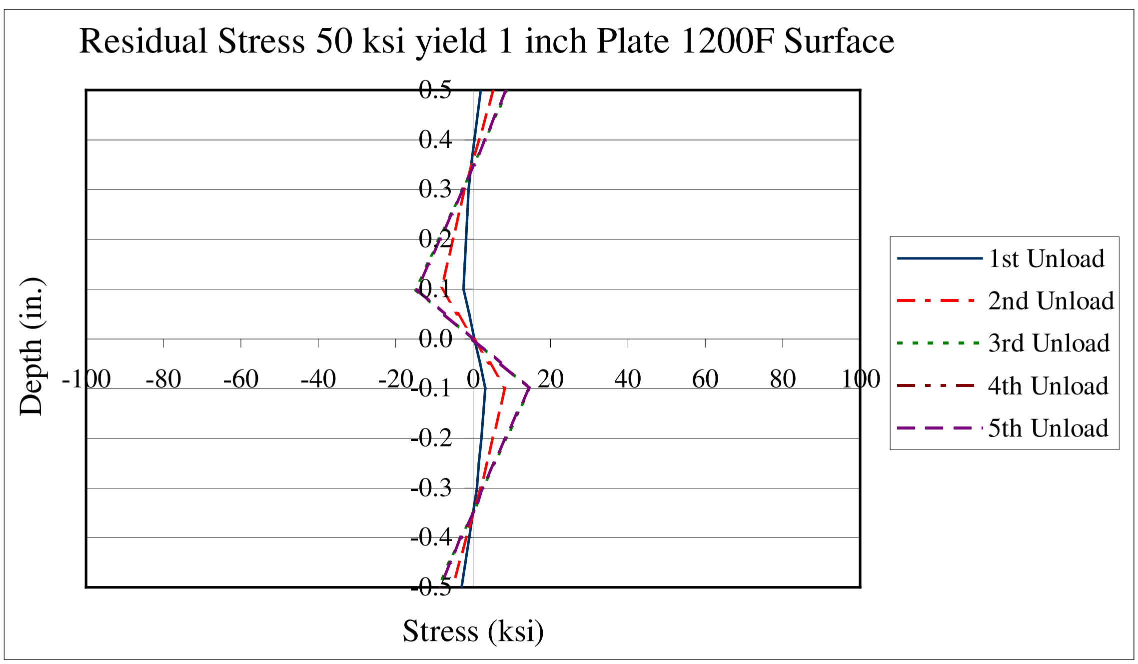

Stress Plots for 50 ksi yield 1 inch Plate 5 Minute Cooling
Depth (in.)
Stress (ksi)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-100
-80
-60
-40
-20
0
20
40
60
80
100
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

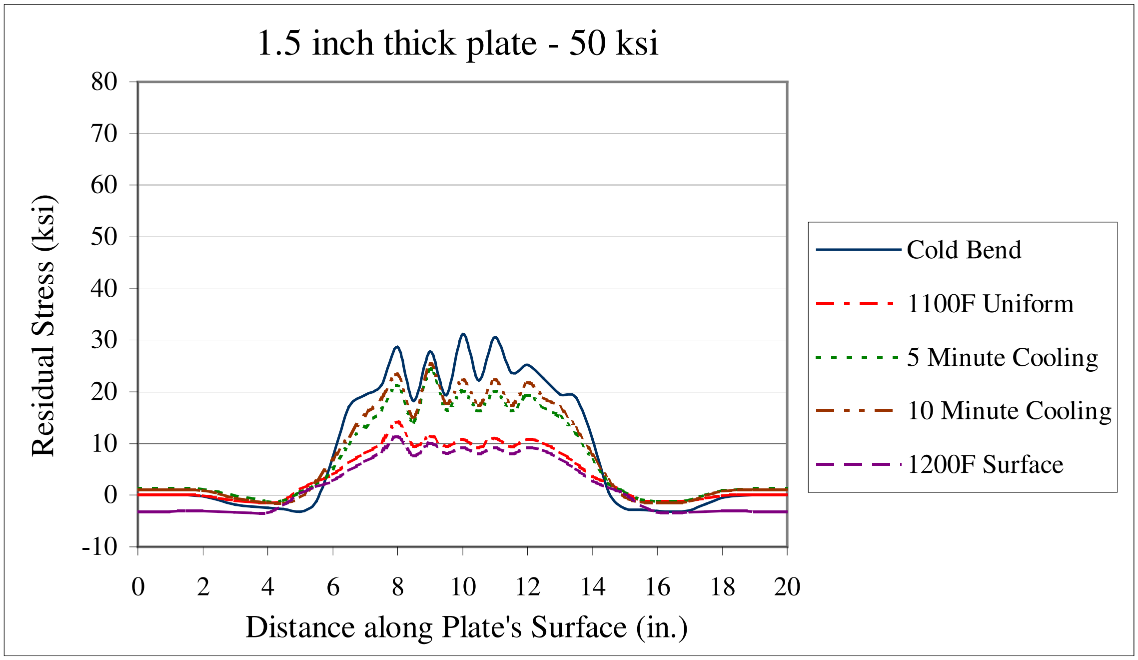

Residual Stress 50 ksi yield 1 inch Plate 5 Minute Cooling
Depth (in.)
Stress (ksi)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-100
-80
-60
-40
-20
0
20
40
60
80
100
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

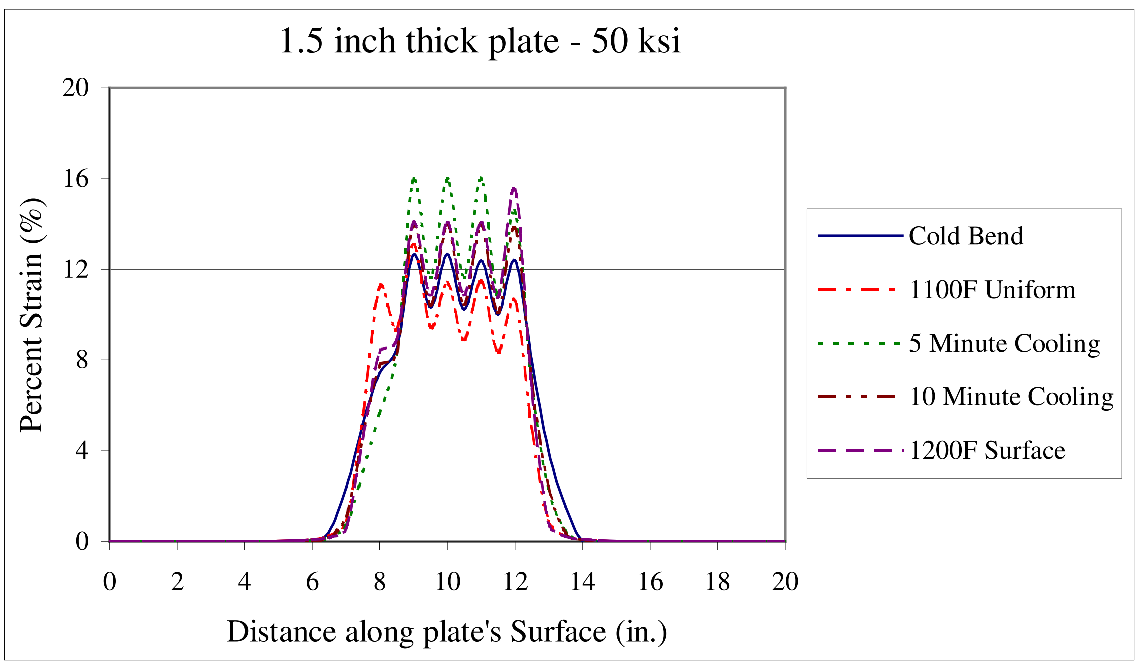

Stress Plots 50 ksi yield 1 inch Plate 10 Minute Cooling
Depth (in.)
Stress (ksi)
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

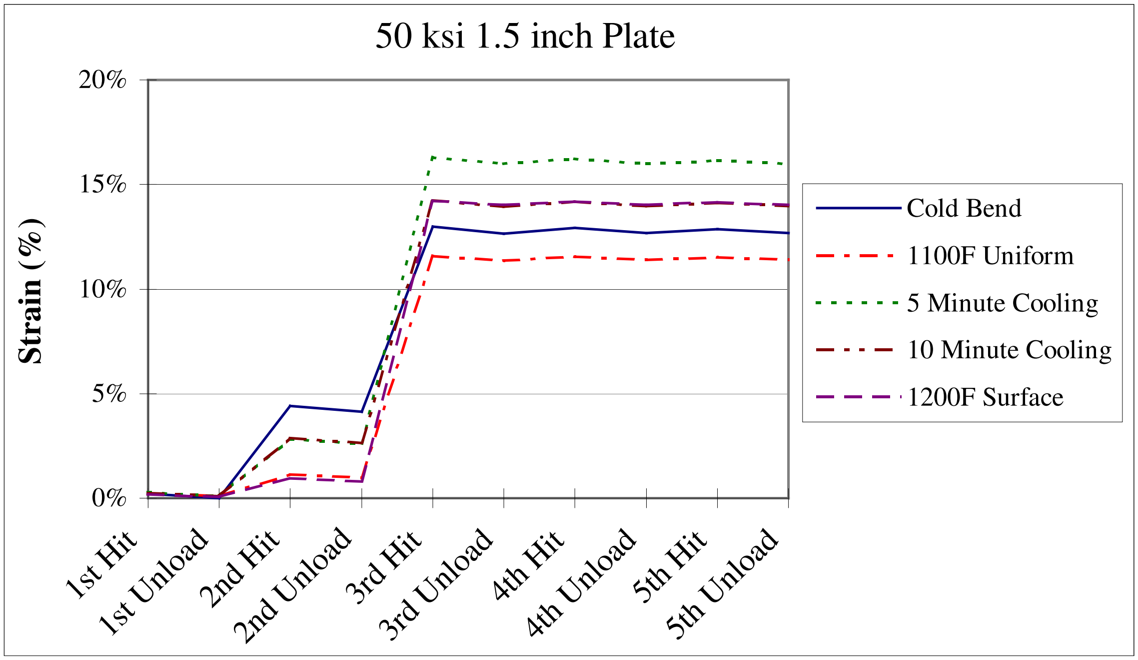

Residual Stress 50 ksi yield 1 inch Plate 10 Minute Cooling
Depth (in.)
Stress (ksi)
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload


Stress Plots for 50 ksi yield 1 inch Plate 1200F Surface
Depth (in.)
Stress (ksi)
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

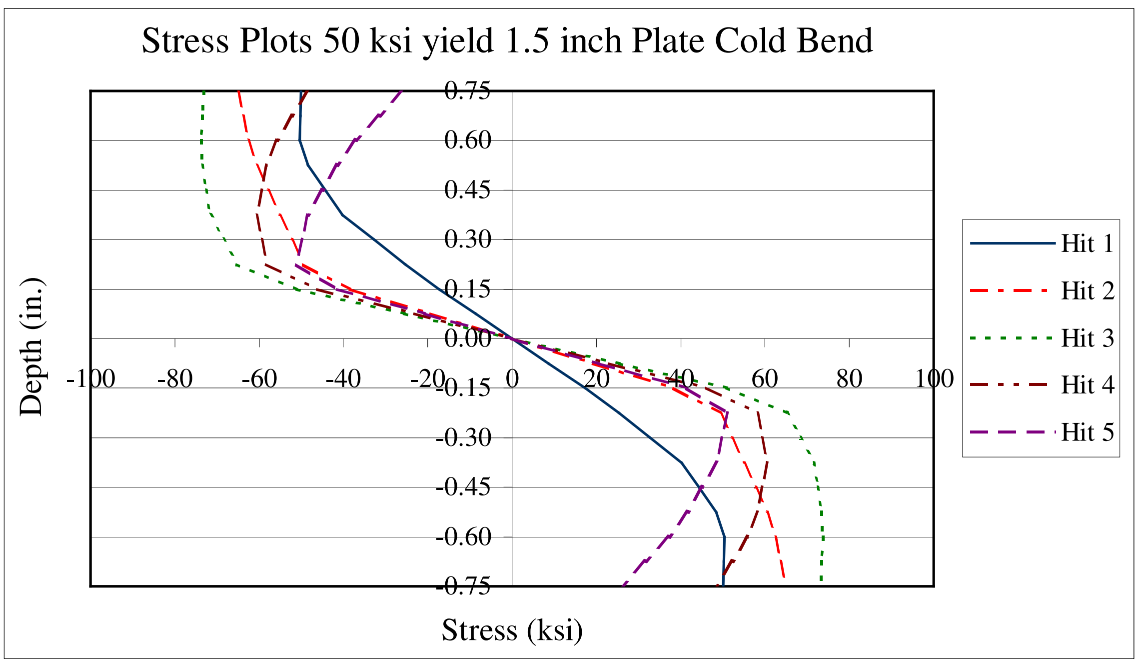

Residual Stress 50 ksi yield 1 inch Plate 1200F Surface
Depth (in.)
Stress (ksi)
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload


1.5 inch thick plate - 50 ksi
Residual Stress (ksi)
80
70
60
50
40
30
20
10
0
-10
0
2
4
6
8
10
12
14
16
18
20
Distance along Plate's Surface (in.)
Cold Bend
1100F Uniform
5 Minute Cooling
10 Minute Cooling
1200F Surface

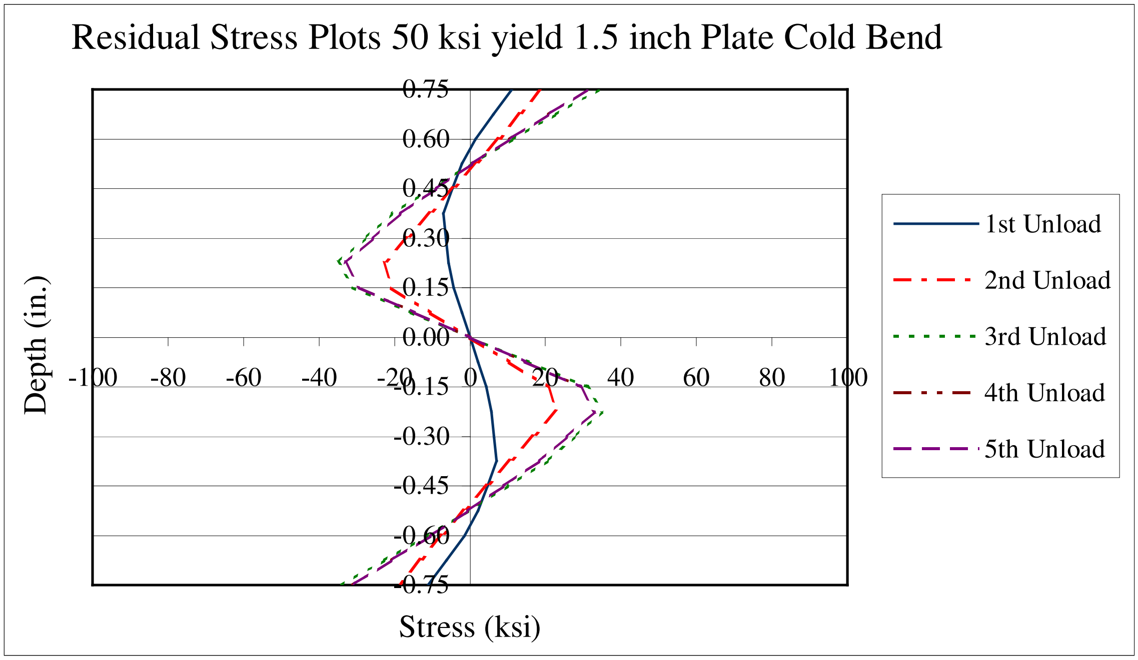

1.5 inch thick plate - 50 ksi
Percent Strain (%)
20
16
12
8
4
0
0
2
4
6
8
10
12
14
16
18
20
Distance along plate's Surface (in.)
Cold Bend
1100F Uniform
5 Minute Cooling
10 Minute Cooling
1200F Surface

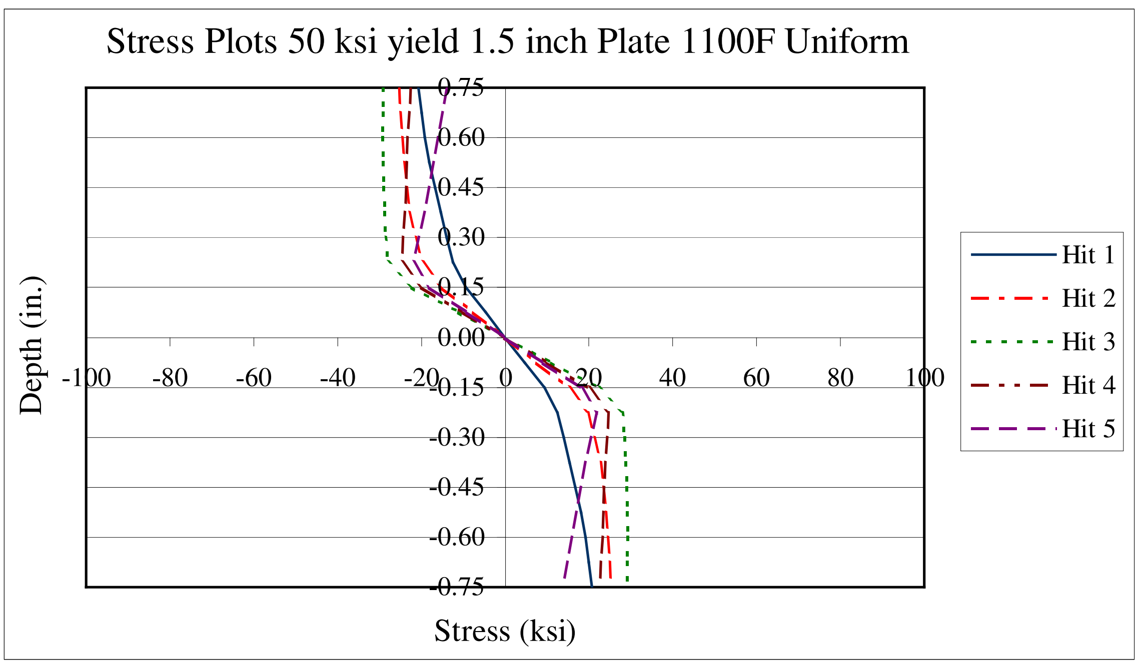


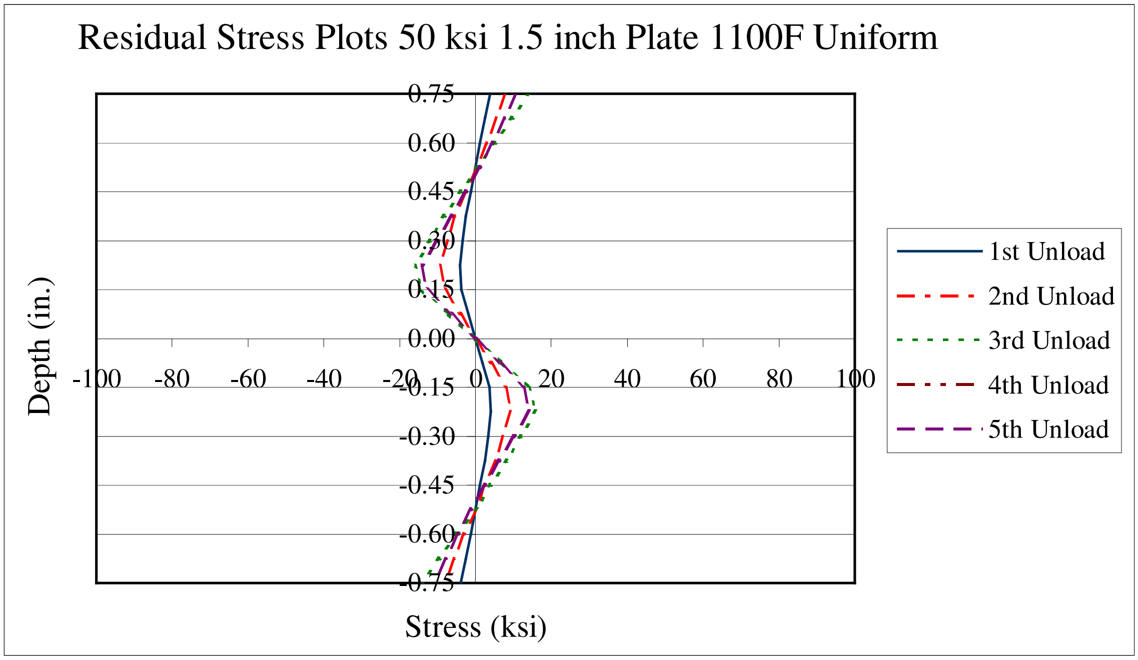
50 ksi 1.5 inch Plate
Strain (%)
20%
15%
10%
5%
0%
1st Hit
1st Unload
2nd Hit
2nd Unload
3rd Hit
3rd Unload
4th Hit
4th Unload
5th Hit
5th Unload
Cold Bend
1100F Uniform
5 Minute Cooling
10 Minute Cooling
1200F Surface

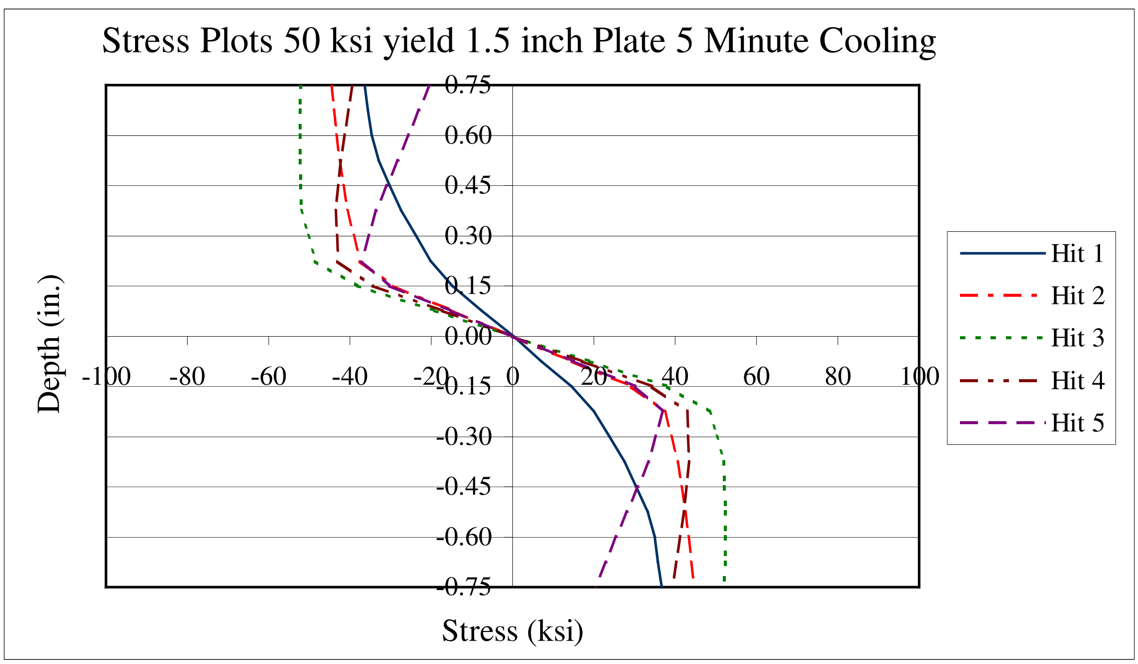


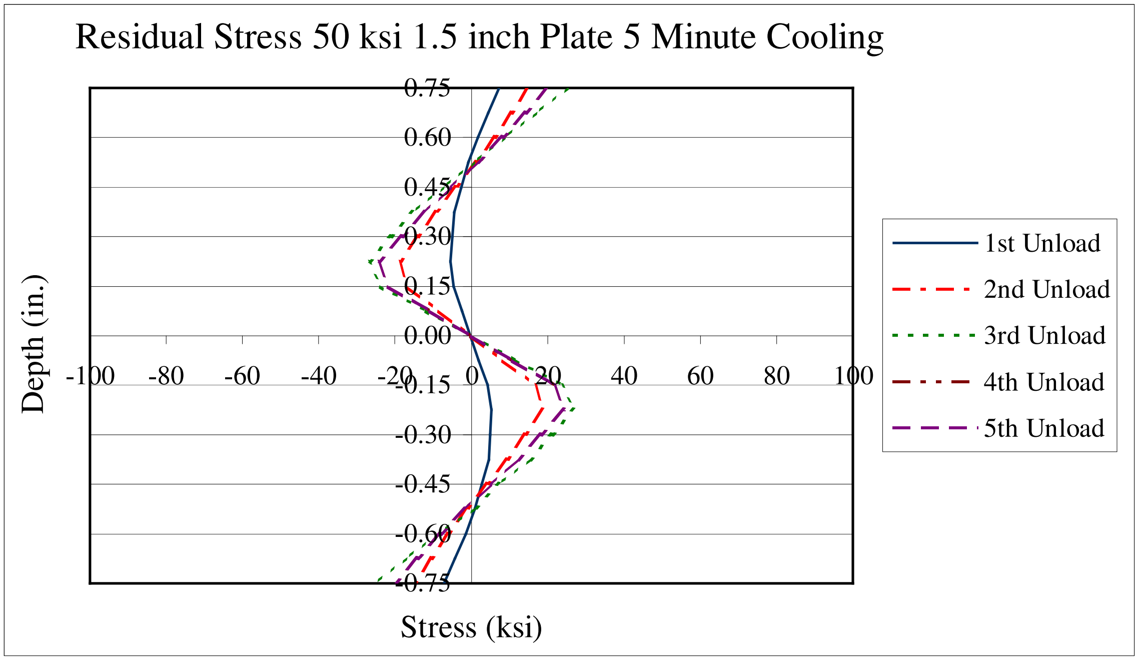
Stress Plots 50 ksi yield 1.5 inch Plate Cold Bend
Depth (in.)
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
Stress (ksi)
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

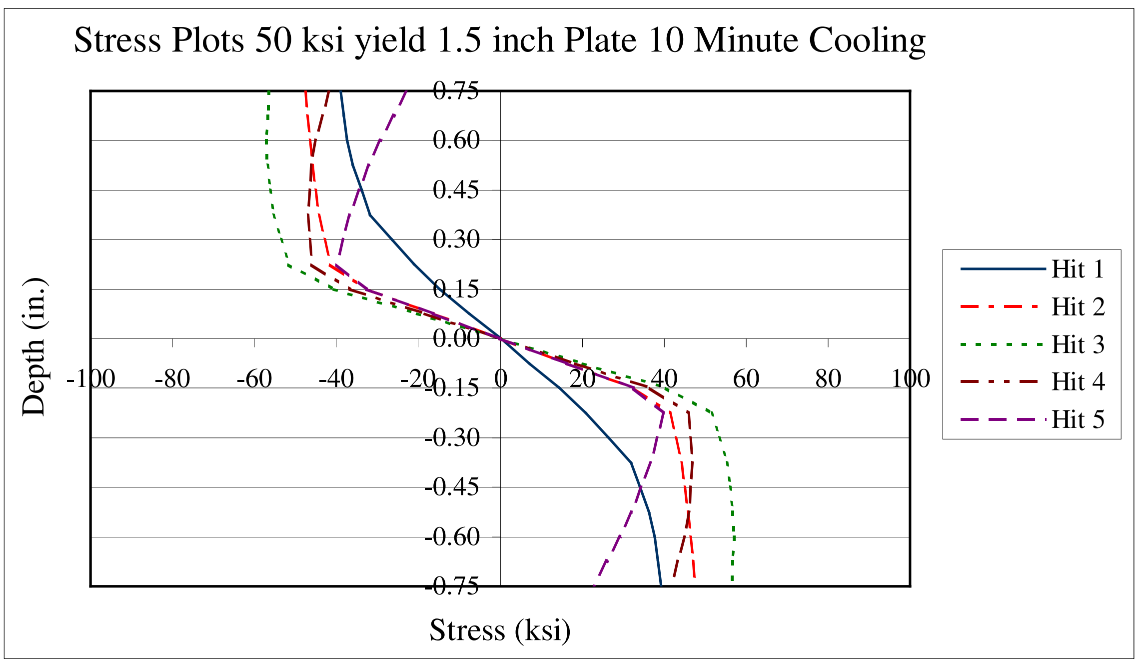

Residual Stress Plots 50 ksi yield 1.5 inch Plate Cold Bend
Depth (in.)
Stress (ksi)
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

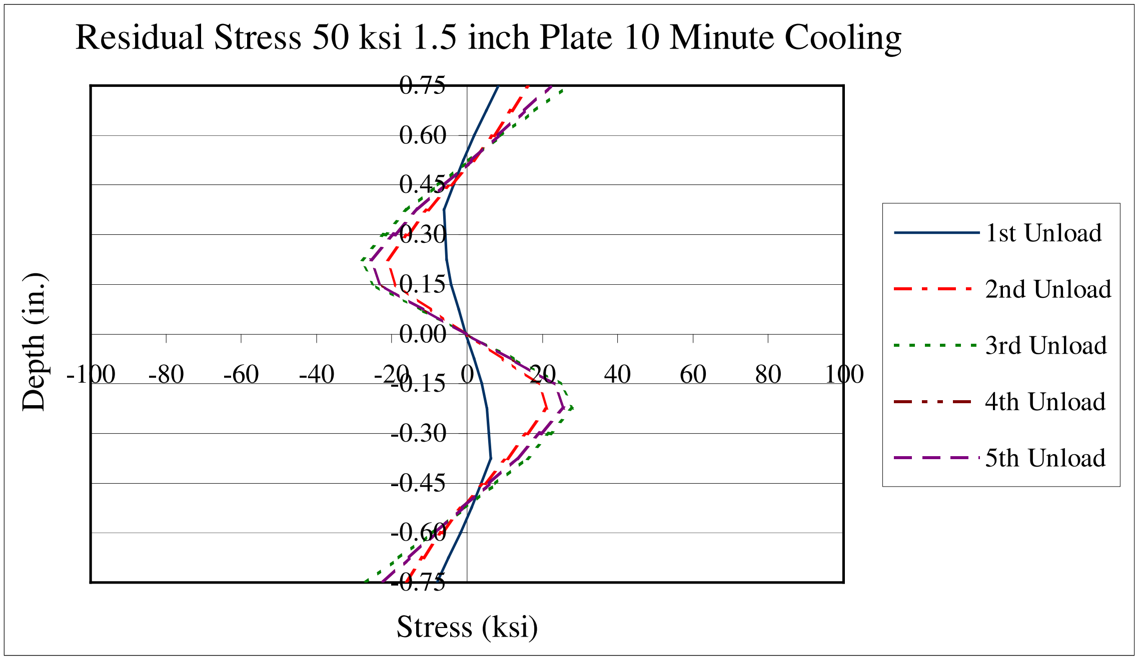

Stress Plots 50 ksi yield 1.5 inch Plate 1100F Uniform
Depth (in.)
Stress (ksi)
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

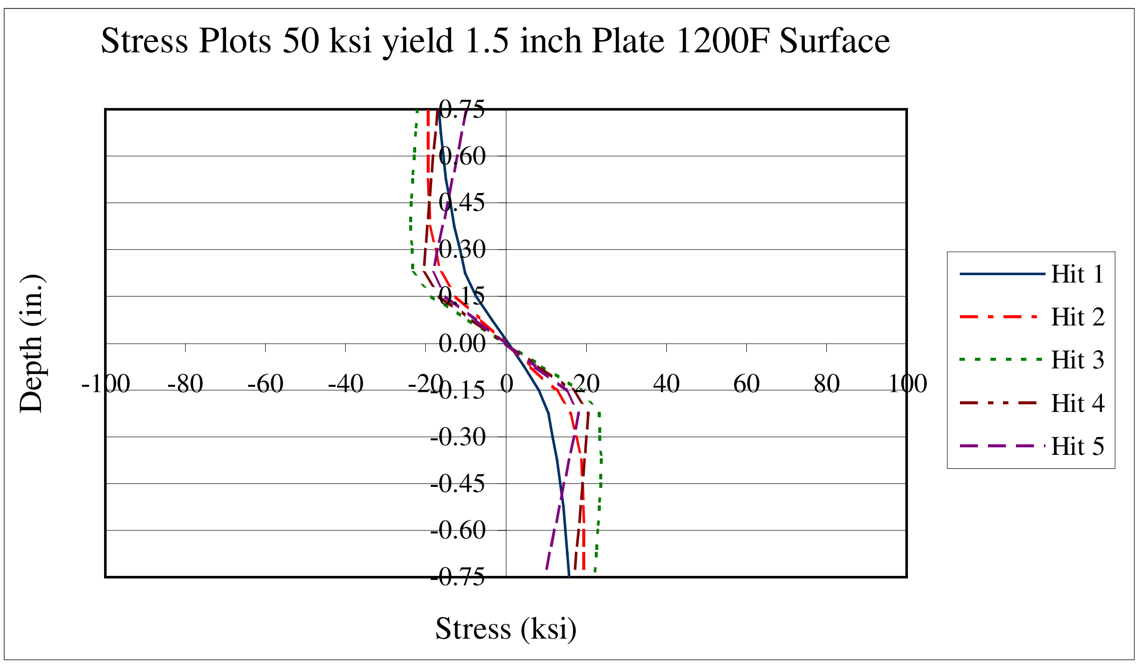

Residual Stress Plots 50 ksi 1.5 inch Plate 1100F Uniform
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

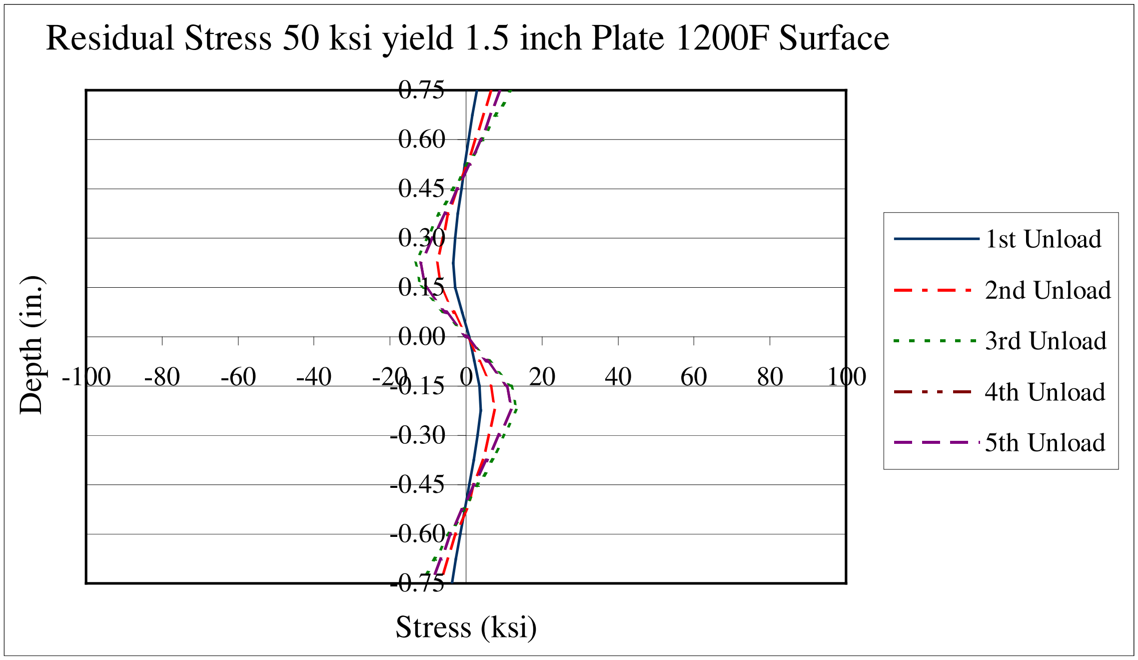

Stress Plots 50 ksi yield 1.5 inch Plate 5 Minute Cooling
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

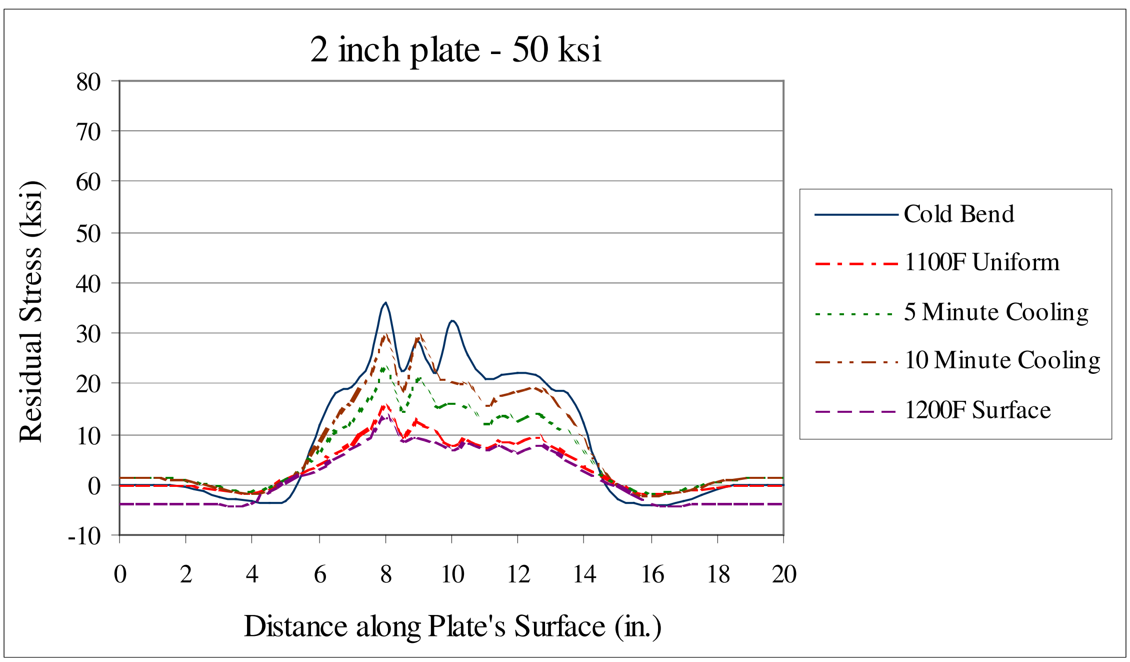

Residual Stress 50 ksi 1.5 inch Plate 5 Minute Cooling
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

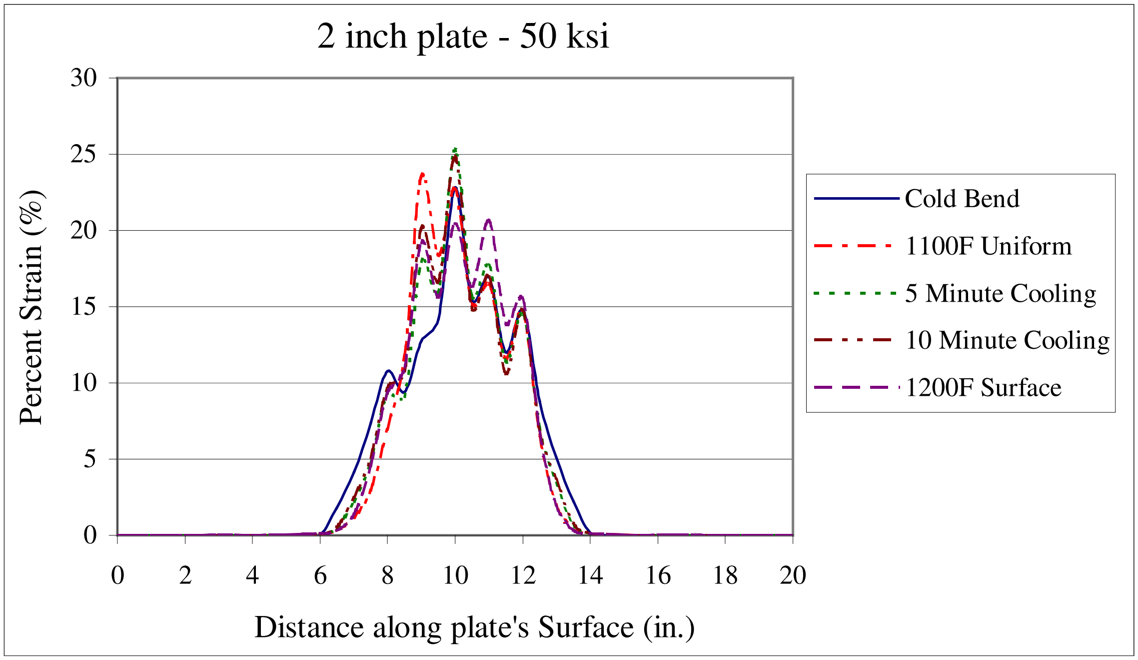

Stress Plots 50 ksi yield 1.5 inch Plate 10 Minute Cooling
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

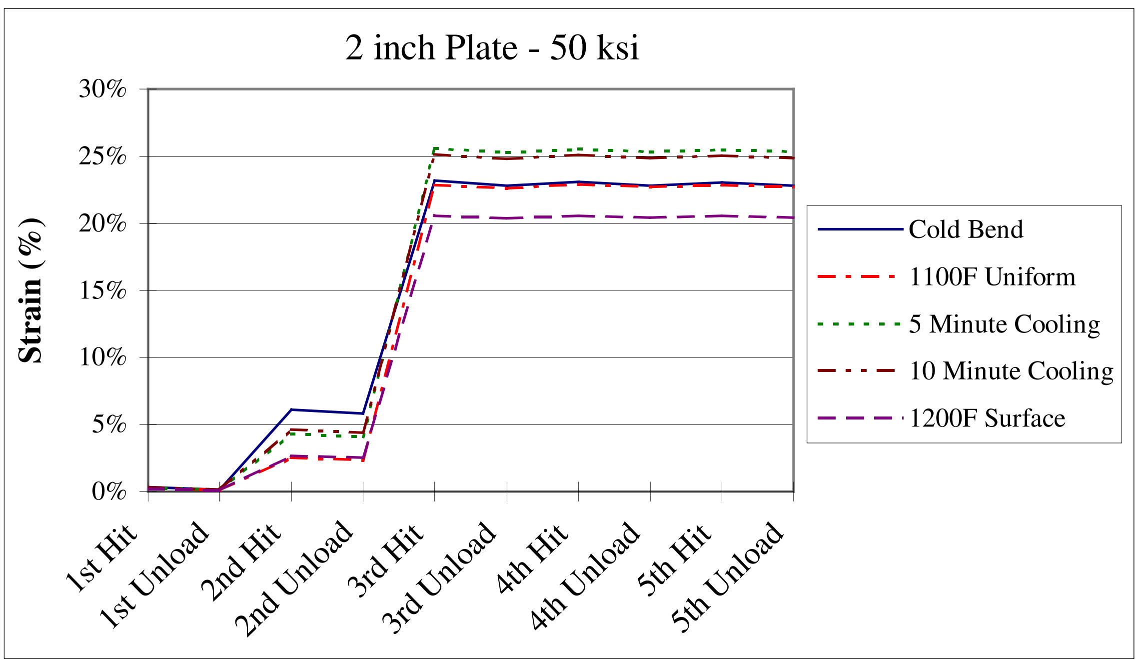

Residual Stress 50 ksi 1.5 inch Plate 10 Minute Cooling
Depth (in.)
Stress (ksi)
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

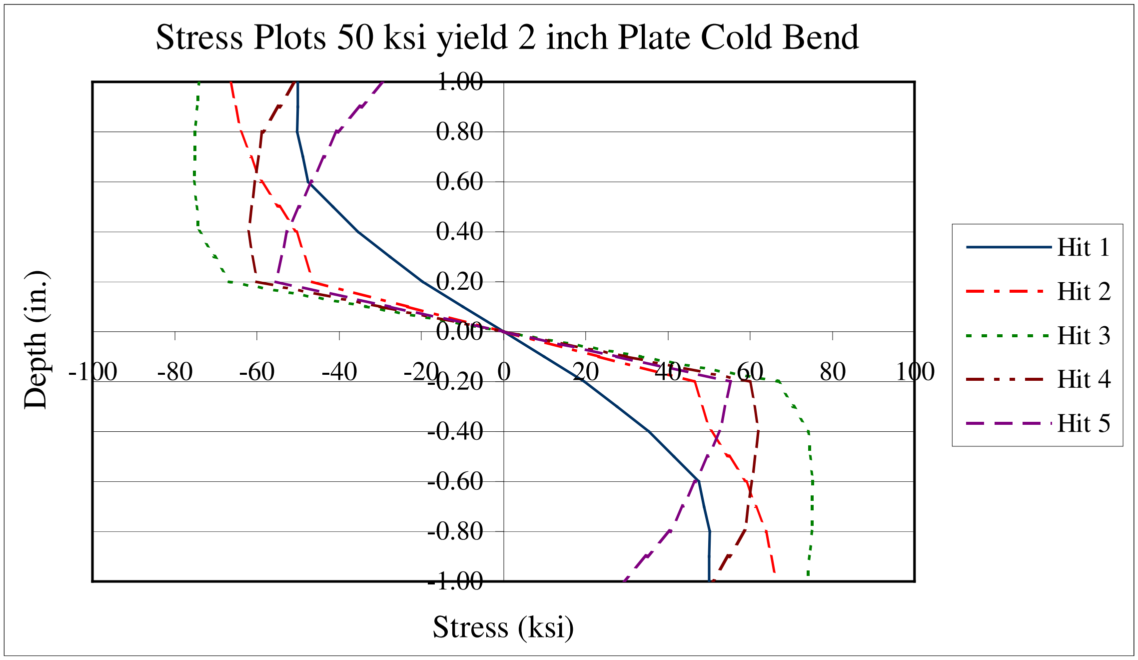

Stress Plots 50 ksi yield 1.5 inch Plate 1200F Surface
Depth (in.)
Stress (ksi)
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5


Residual Stress 50 ksi yield 1.5 inch Plate 1200F Surface
Depth (in.)
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
Stress (ksi)
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

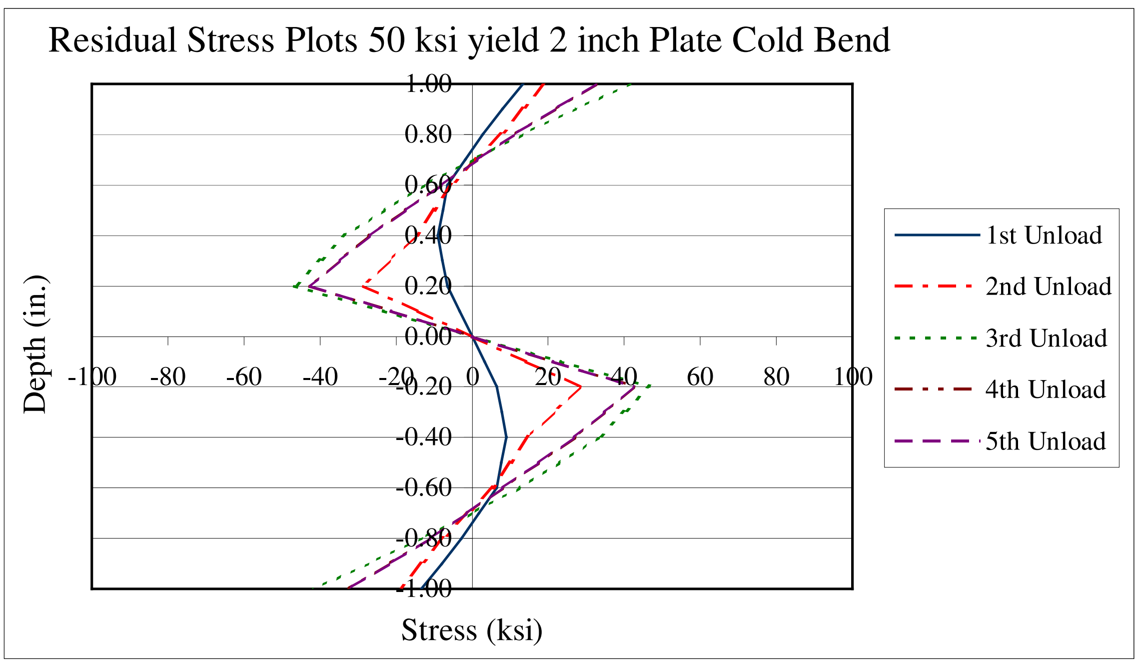

2 inch plate - 50 ksi
Residual Stress (ksi)
80
70
60
50
40
30
20
10
0
-10
0
2
4
6
8
10
12
14
16
18
20
Distance along Plate's Surface (in.)
Cold Bend
1100F Uniform
5 Minute Cooling
10 Minute Cooling
1200F Surface


2 inch plate - 50 ksi
Percent Strain (%)
30
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
20
Distance along plate's Surface (in.)
Cold Bend
1100F Uniform
5 Minute Cooling
10 Minute Cooling
1200F Surface

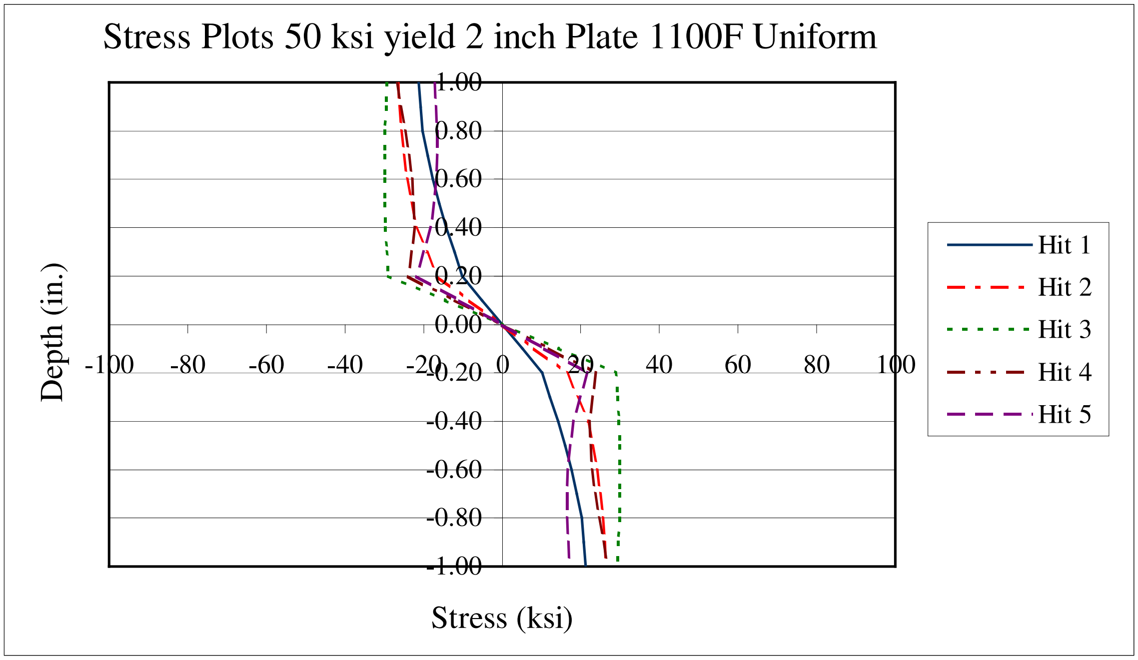

2 inch Plate - 50 ksi
Strain (%)
30%
25%
20%
15%
10%
5%
0%
1st Hit
1st Unload
2nd Hit
2nd Unload
3rd Hit
3rd Unload
4th Hit
4th Unload
5th Hit
5th Unload
Cold Bend
1100F Uniform
5 Minute Cooling
10 Minute Cooling
1200F Surface

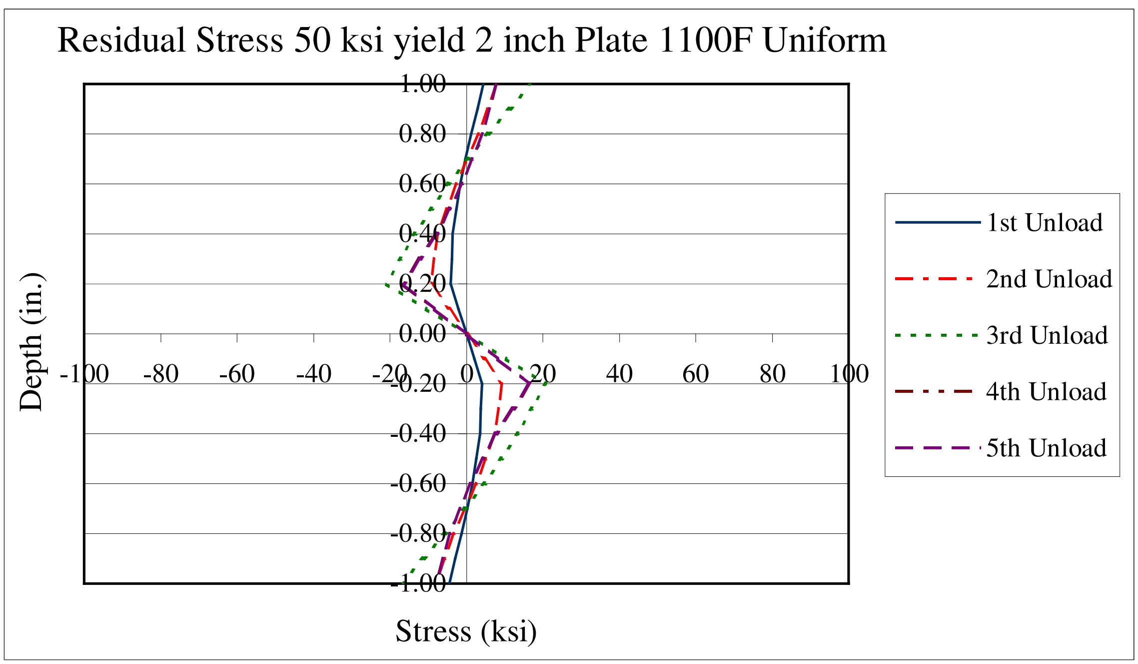


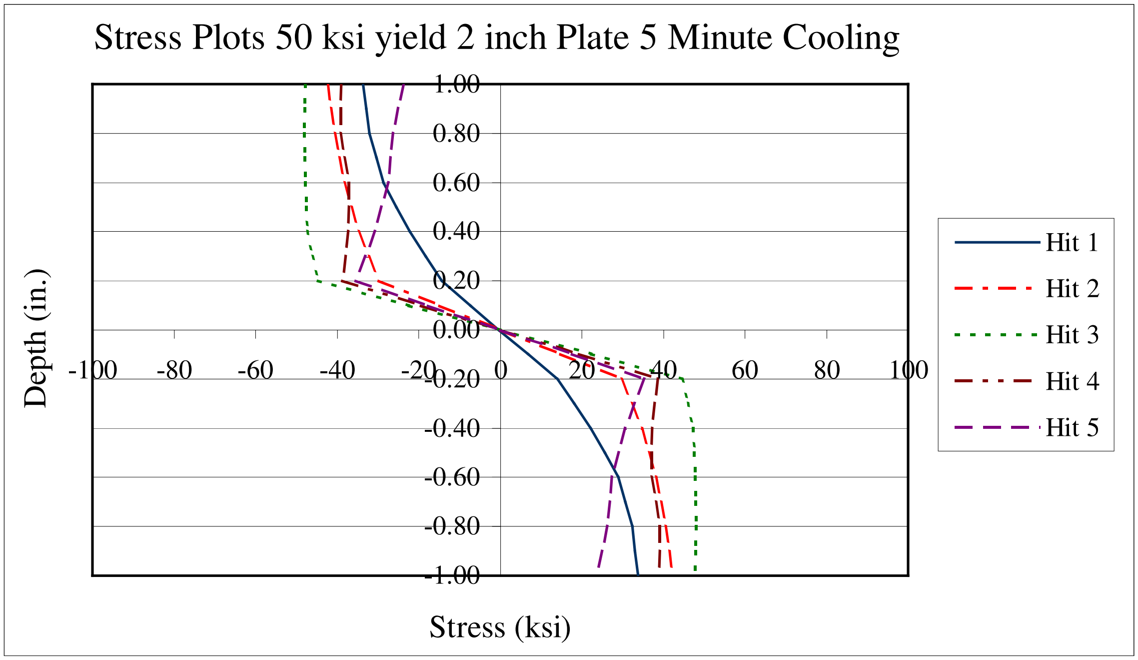
Stress Plots 50 ksi yield 2 inch Plate Cold Bend
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5



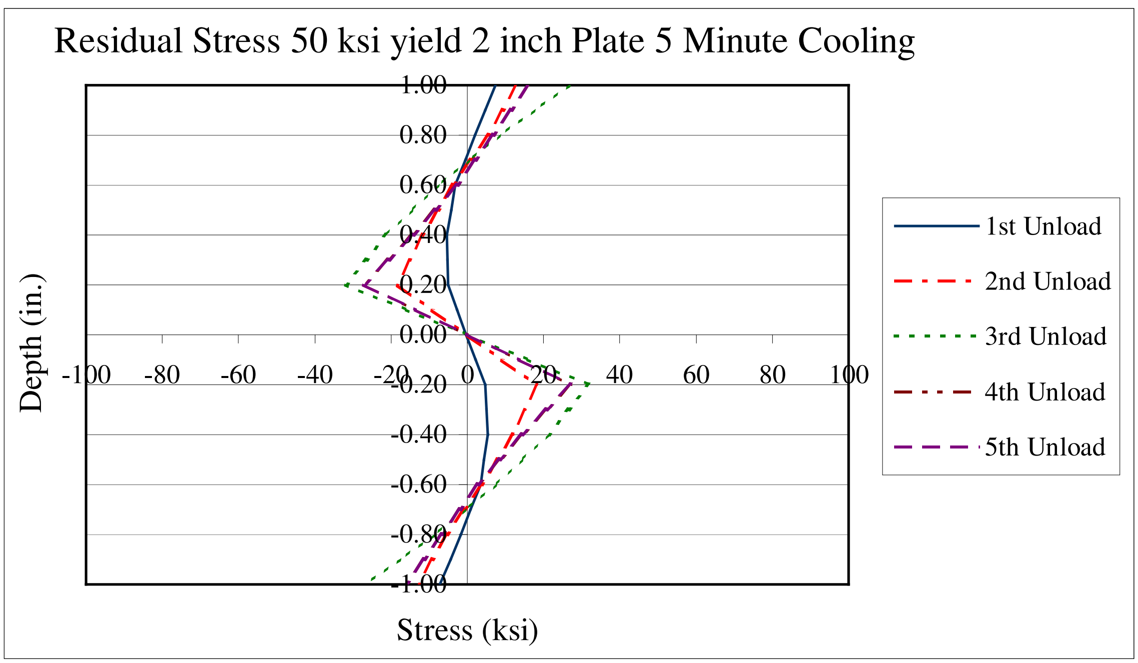
Residual Stress Plots 50 ksi yield 2 inch Plate Cold Bend
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload


Stress Plots 50 ksi yield 2 inch Plate 1100F Uniform
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

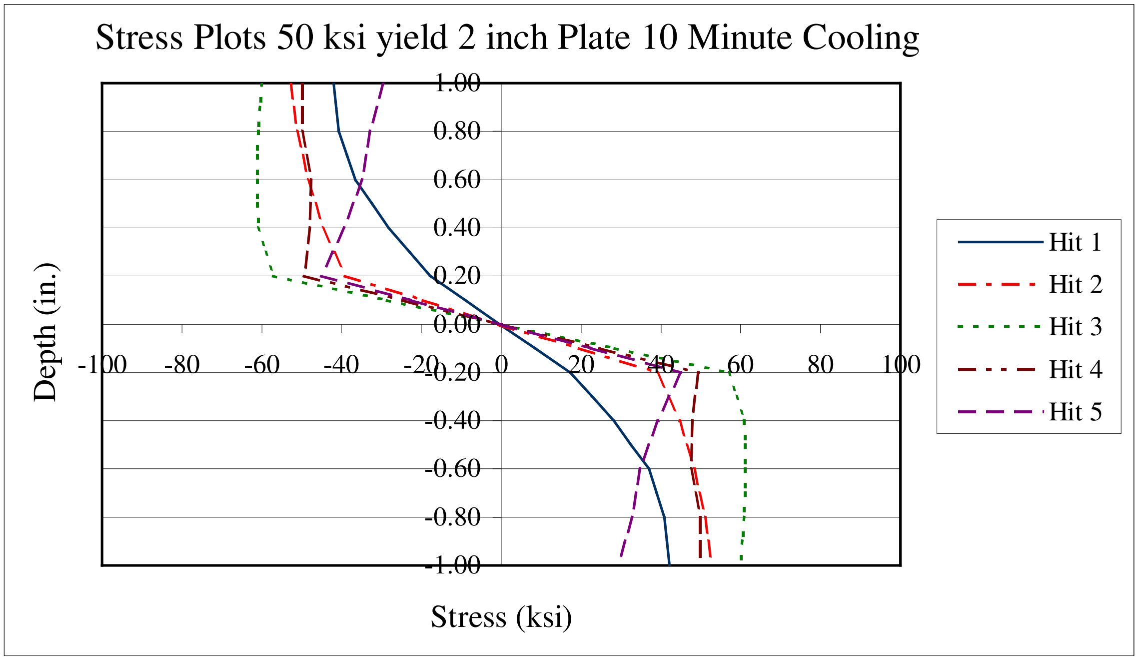

Residual Stress 50 ksi yield 2 inch Plate 1100F Uniform
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

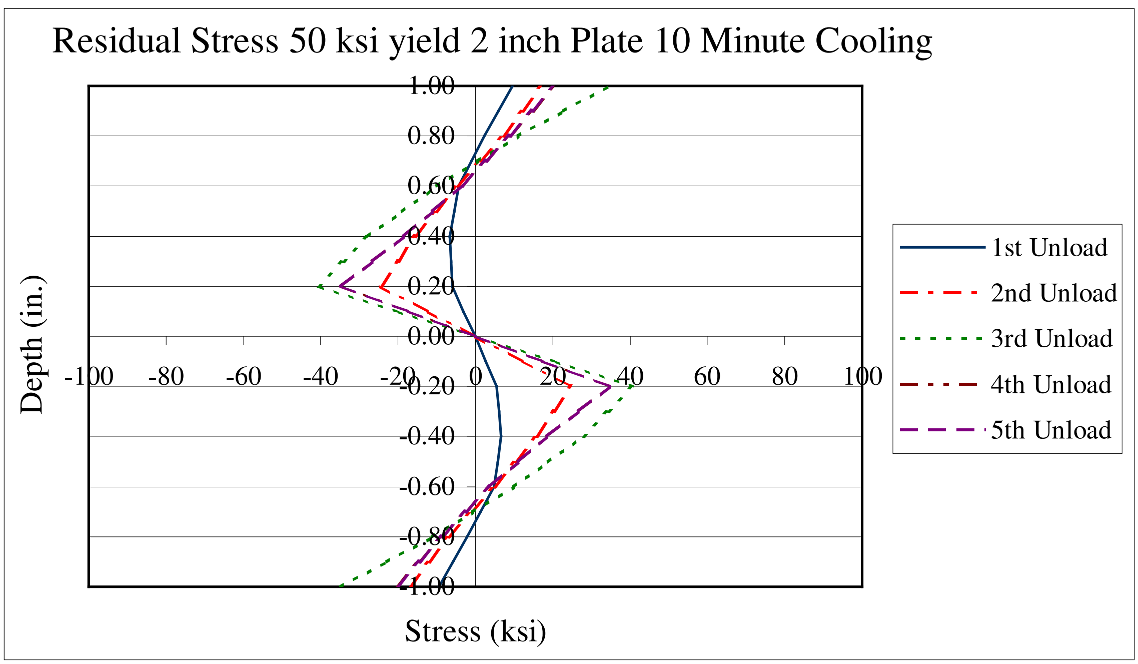


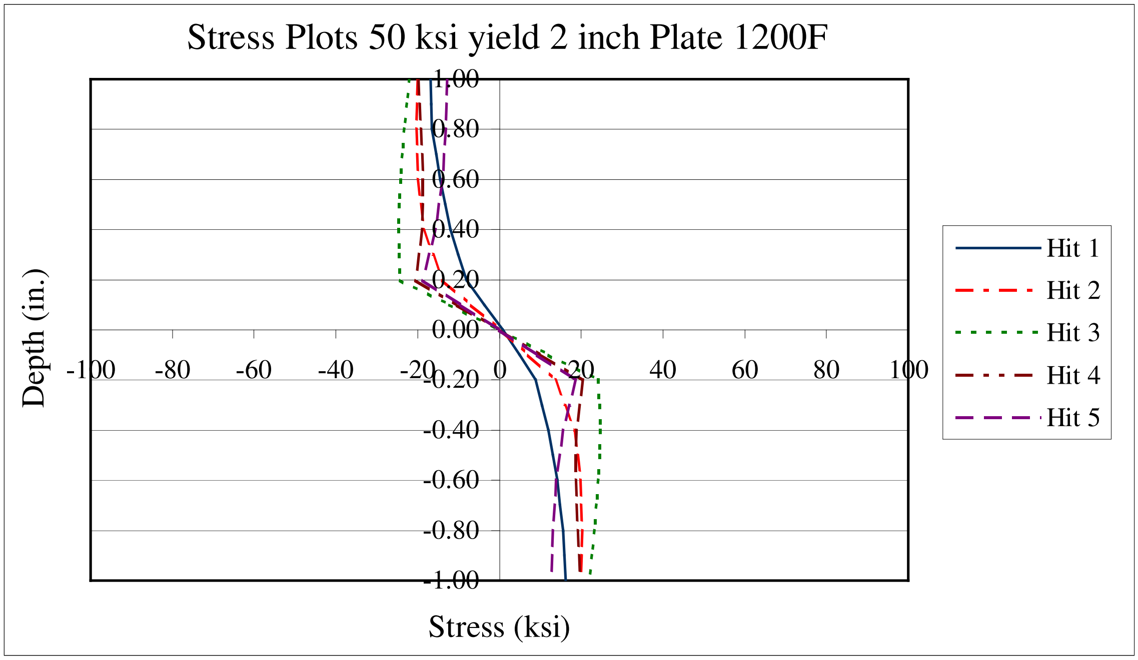
Stress Plots 50 ksi yield 2 inch Plate 5 Minute Cooling
Depth (in.)
Stress (ksi)
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-100
-80
-60
-40
-20
0
20
40
60
80
100
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

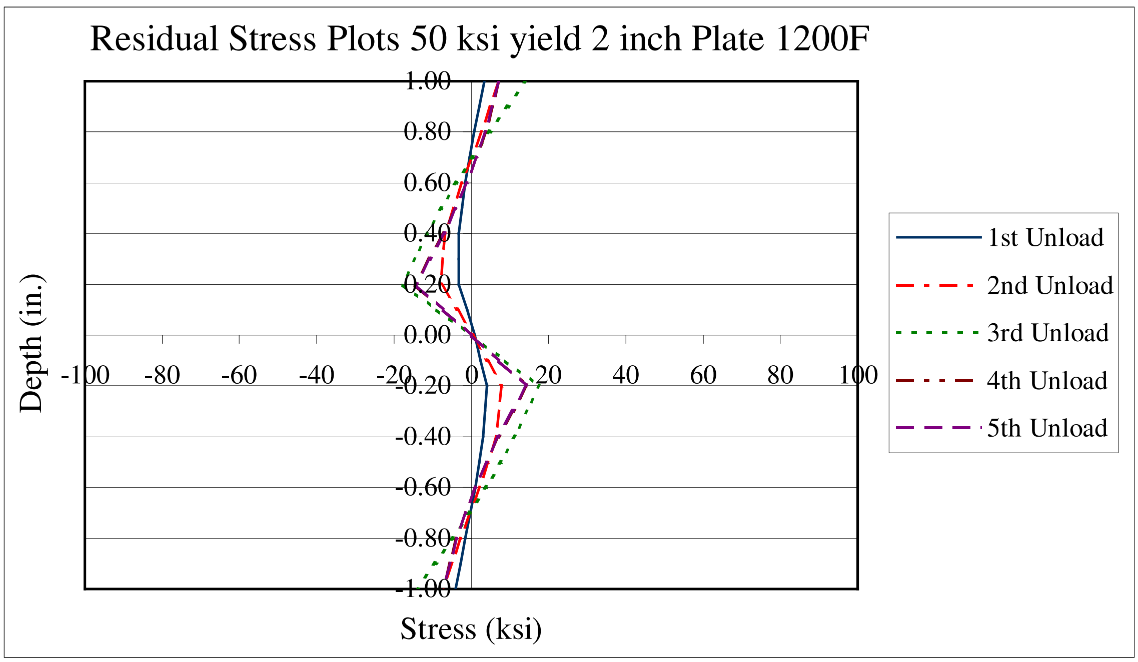


Residual Stress 50 ksi yield 2 inch Plate 5 Minute Cooling
Depth (in.)
Stress (ksi)
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-100
-80
-60
-40
-20
0
20
40
60
80
100
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload


Stress Plots 50 ksi yield 2 inch Plate 10 Minute Cooling
Depth (in.)
Stress (ksi)
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-100
-80
-60
-40
-20
0
20
40
60
80
100
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

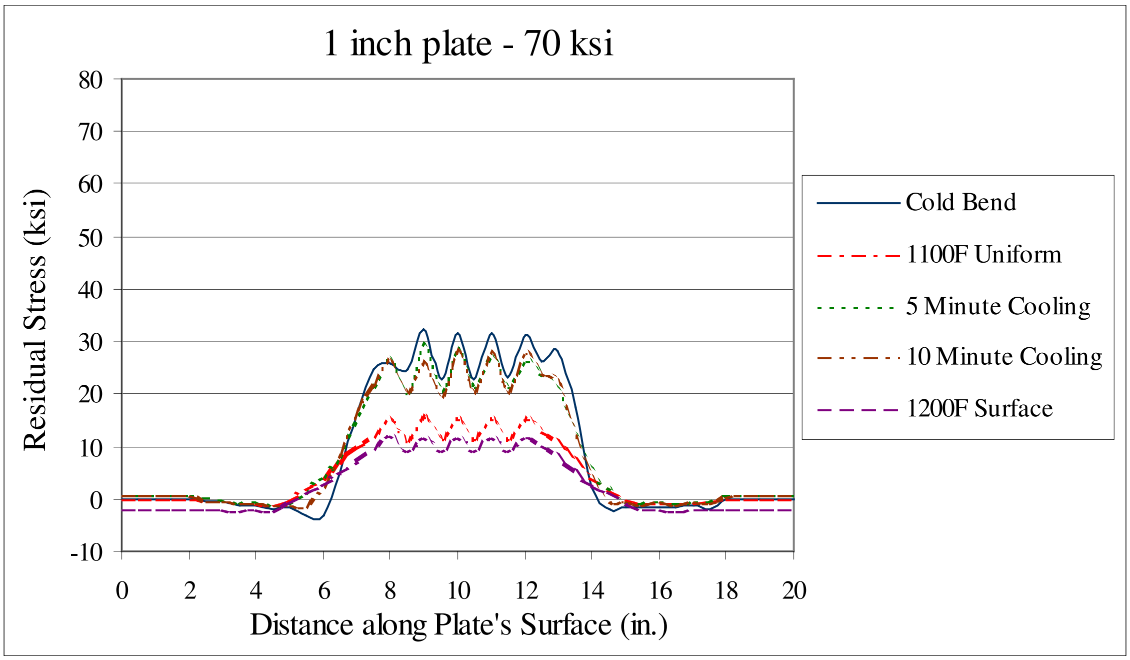

Residual Stress 50 ksi yield 2 inch Plate 10 Minute Cooling
Depth (in.)
Stress (ksi)
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-100
-80
-60
-40
-20
0
20
40
60
80
100
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

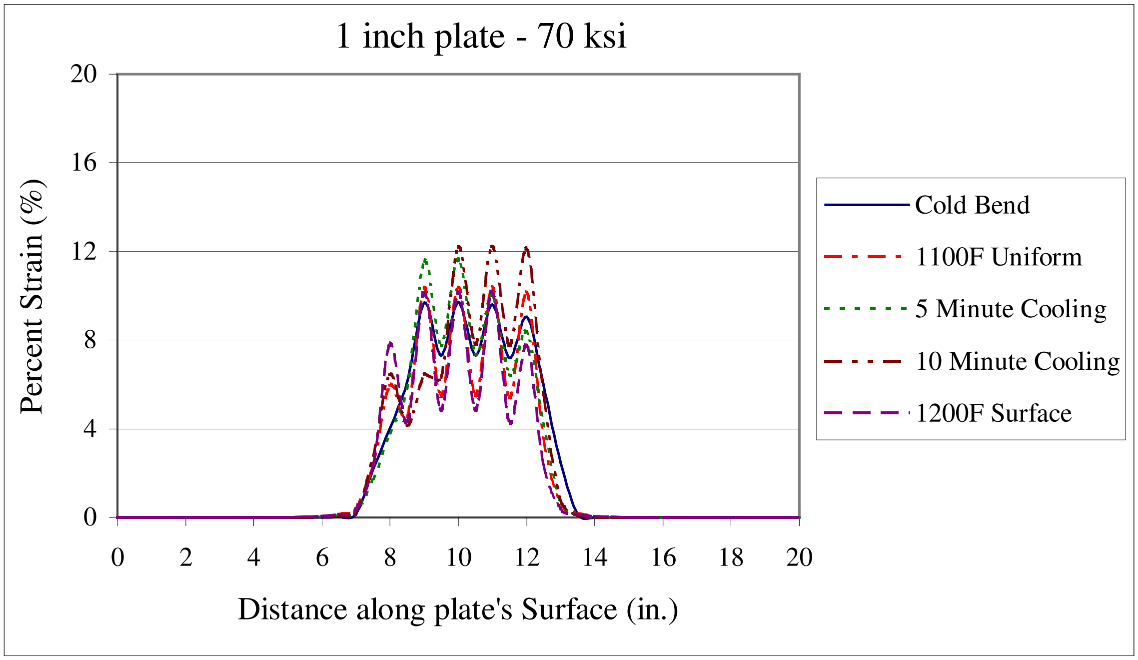

Stress Plots 50 ksi yield 2 inch Plate 1200F
Depth (in.)
Stress (ksi)
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-100
-80
-60
-40
-20
0
20
40
60
80
100
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

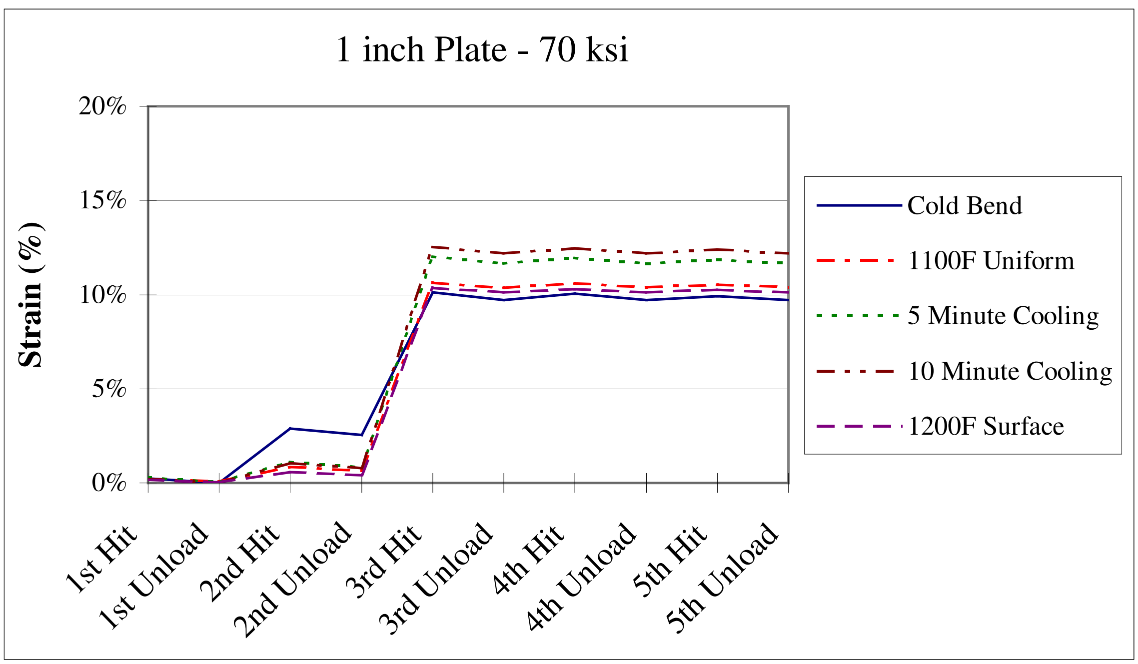

Residual Stress Plots 50 ksi yield 2 inch Plate 1200F
Depth (in.)
Stress (ksi)
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-100
-80
-60
-40
-20
0
20
40
60
80
100
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

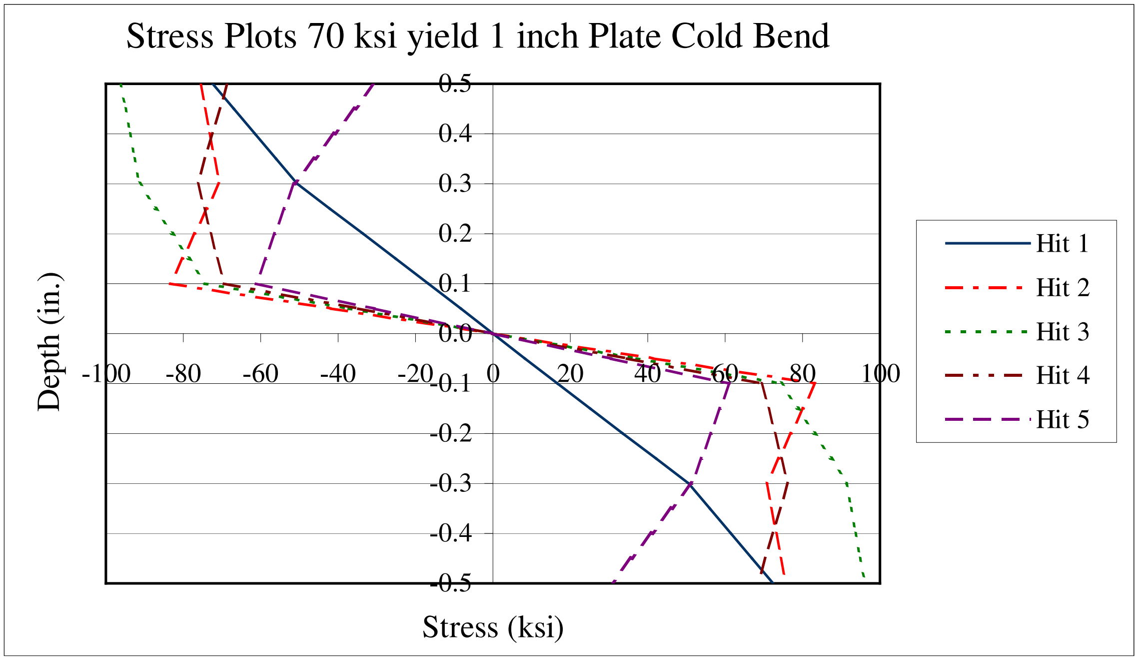
APPENDIX B

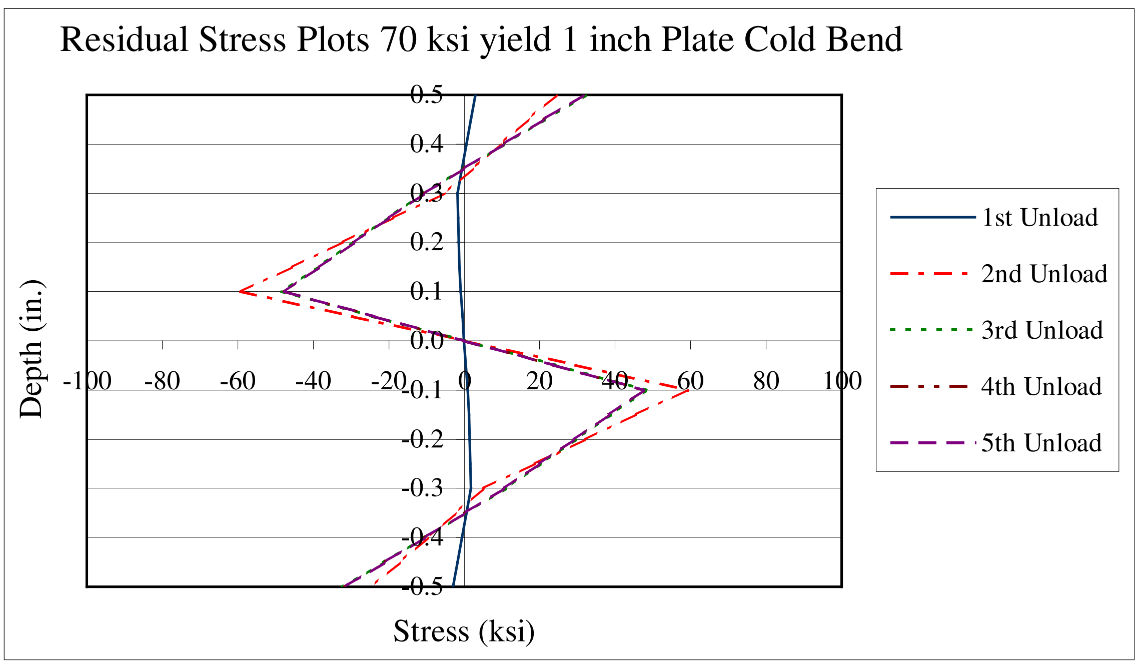
GRADE 70 STRESS AND STRAIN DATA

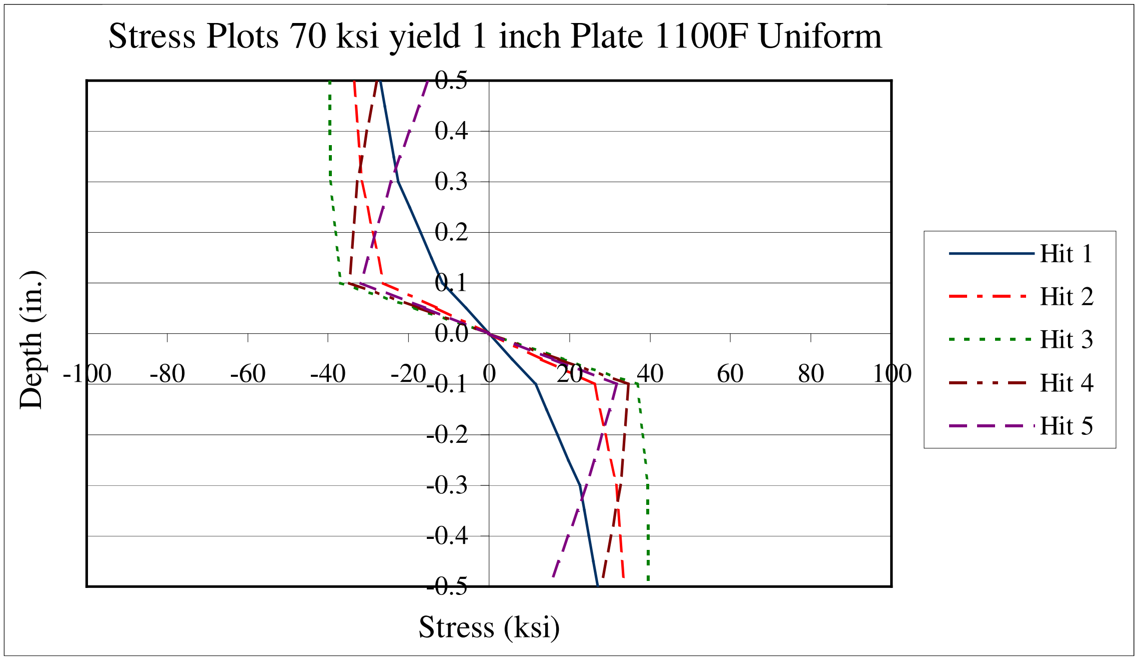


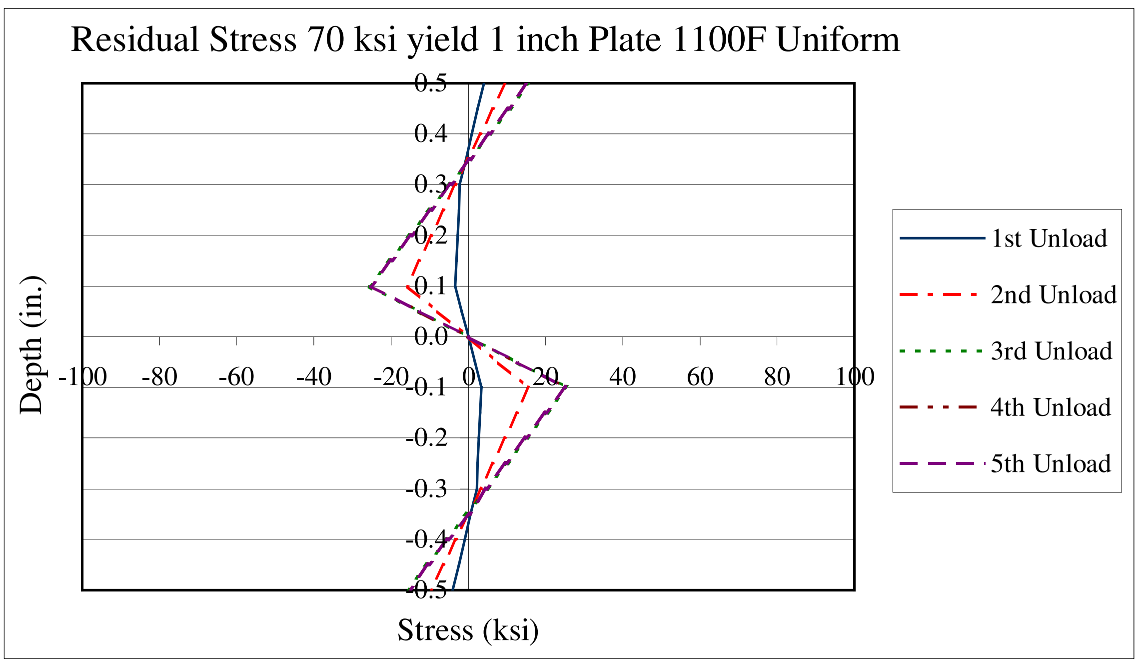

1 inch plate - 70 ksi
Percent Strain (%)
0
4
8
12
16
20
0
2
4
6
8
10
12
14
16
18
20
Distance along plate's Surface (in.)
Cold Bend
1100F Uniform
5 Minute Cooling
10 Minute Cooling
1200F Surface

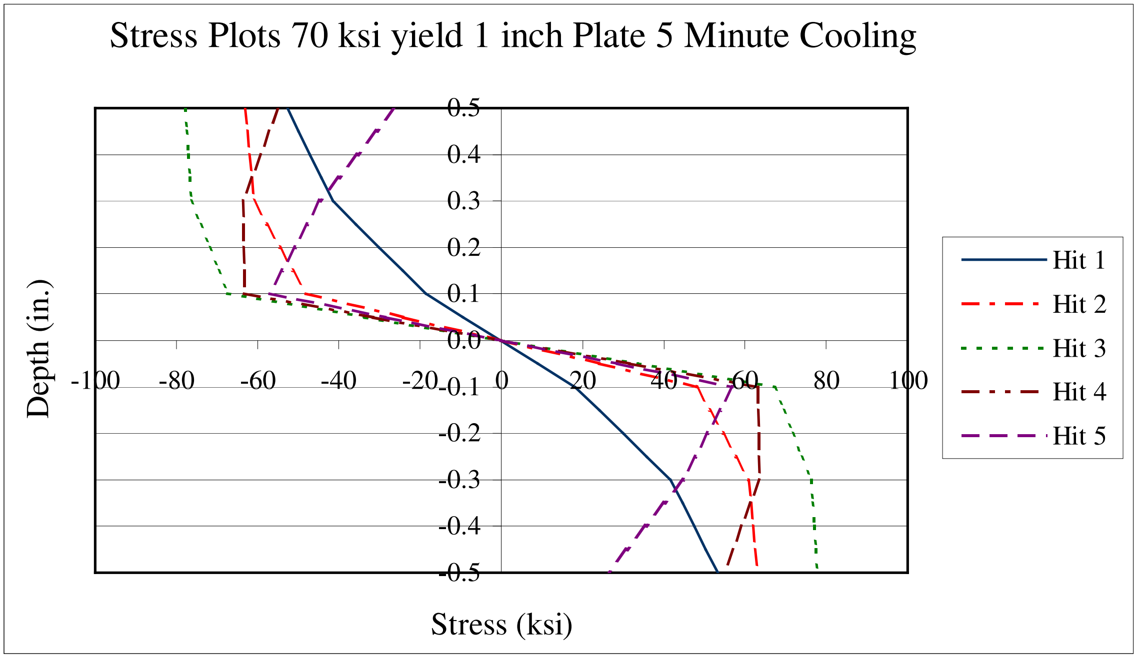

1 inch Plate - 70 ksi
Strain (%)
0%
5%
10%
15%
20%
1st Hit
1st Unload
2nd Hit
2nd Unload
3rd Hit
3rd Unload
4th Hit
4th Unload
5th Hit
5th Unload
Cold Bend
1100F Uniform
5 Minute Cooling
10 Minute Cooling
1200F Surface

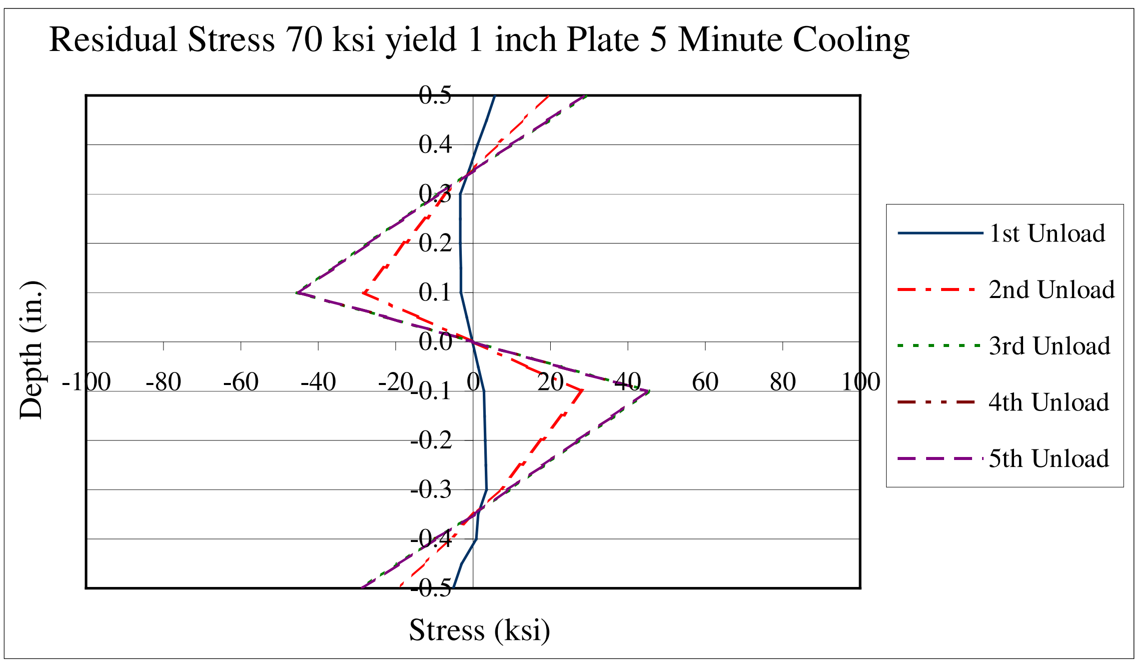

Stress Plots 70 ksi yield 1 inch Plate Cold Bend
Depth (in.)
Stress (ksi)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-100
-80
-60
-40
-20
0
20
40
60
80
100
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

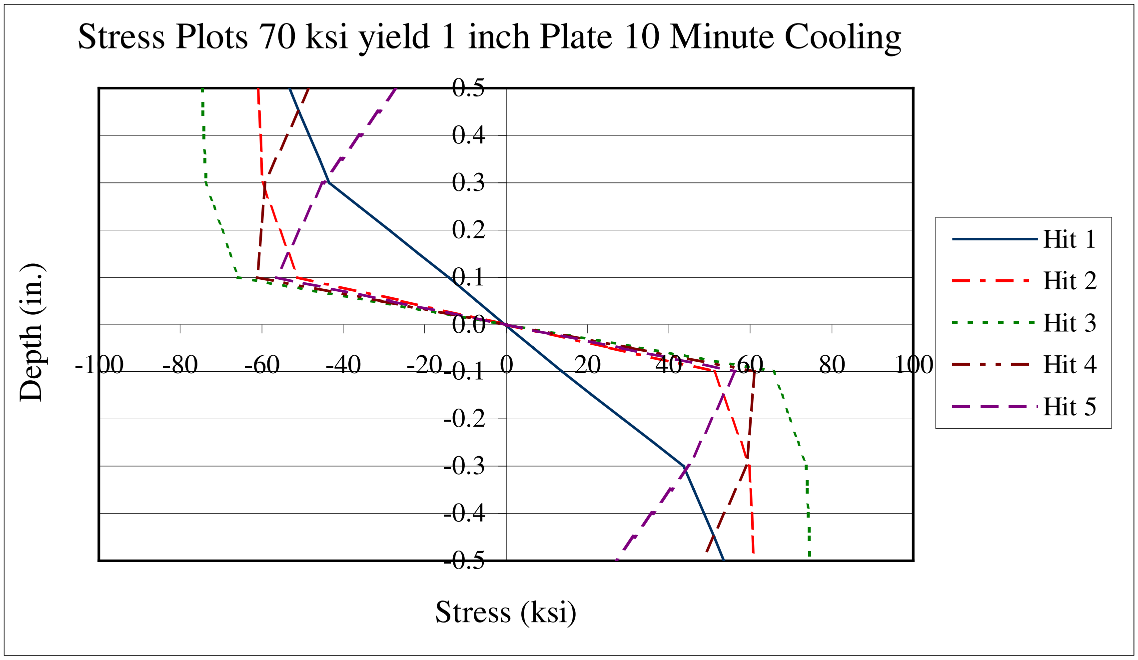

Residual Stress Plots 70 ksi yield 1 inch Plate Cold Bend
Depth (in.)
Stress (ksi)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-100
-80
-60
-40
-20
0
20
40
60
80
100
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

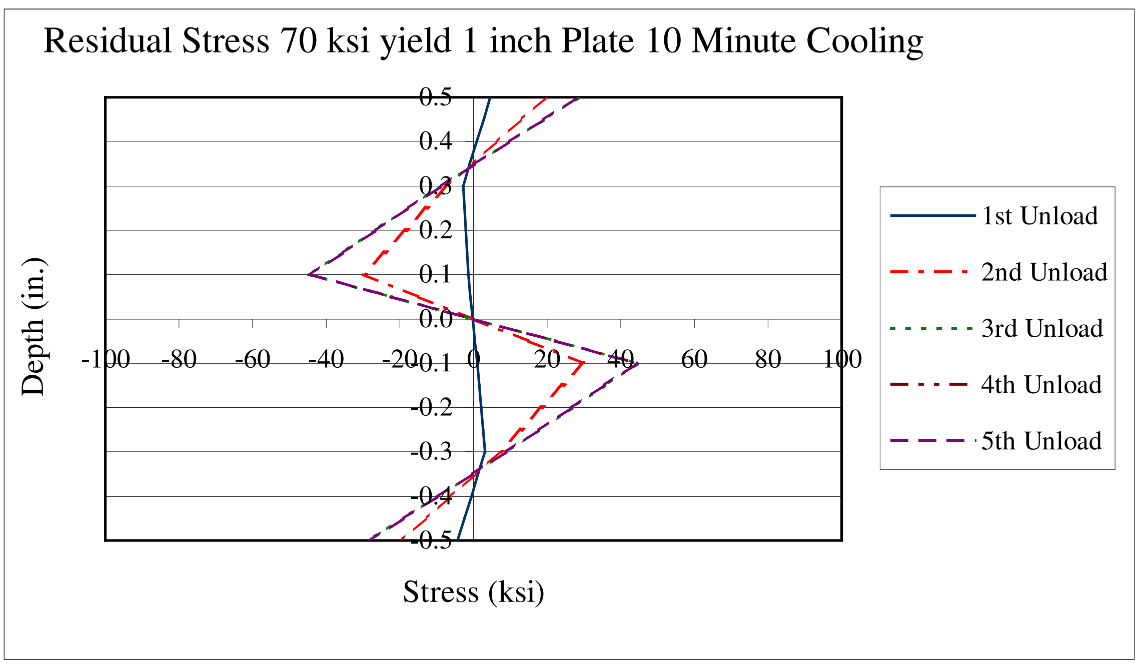

Stress Plots 70 ksi yield 1 inch Plate 1100F Uniform
Depth (in.)
Stress (ksi)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-100
-80
-60
-40
-20
0
20
40
60
80
100
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

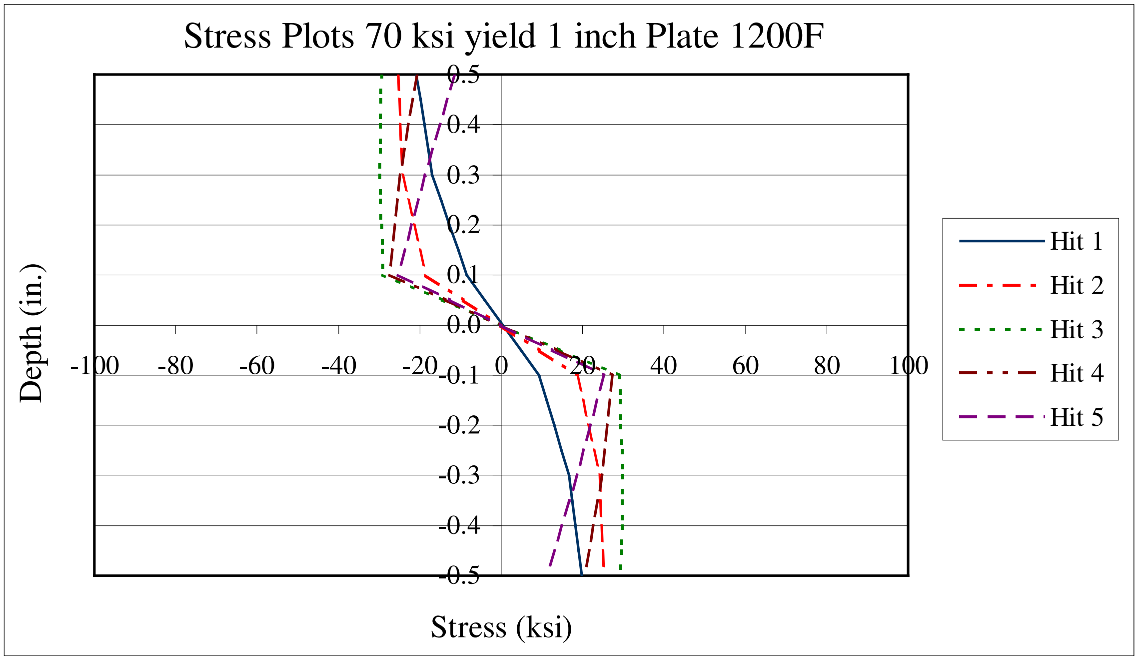

Residual Stress 70 ksi yield 1 inch Plate 1100F Uniform
Depth (in.)
Stress (ksi)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-100
-80
-60
-40
-20
0
20
40
60
80
100
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

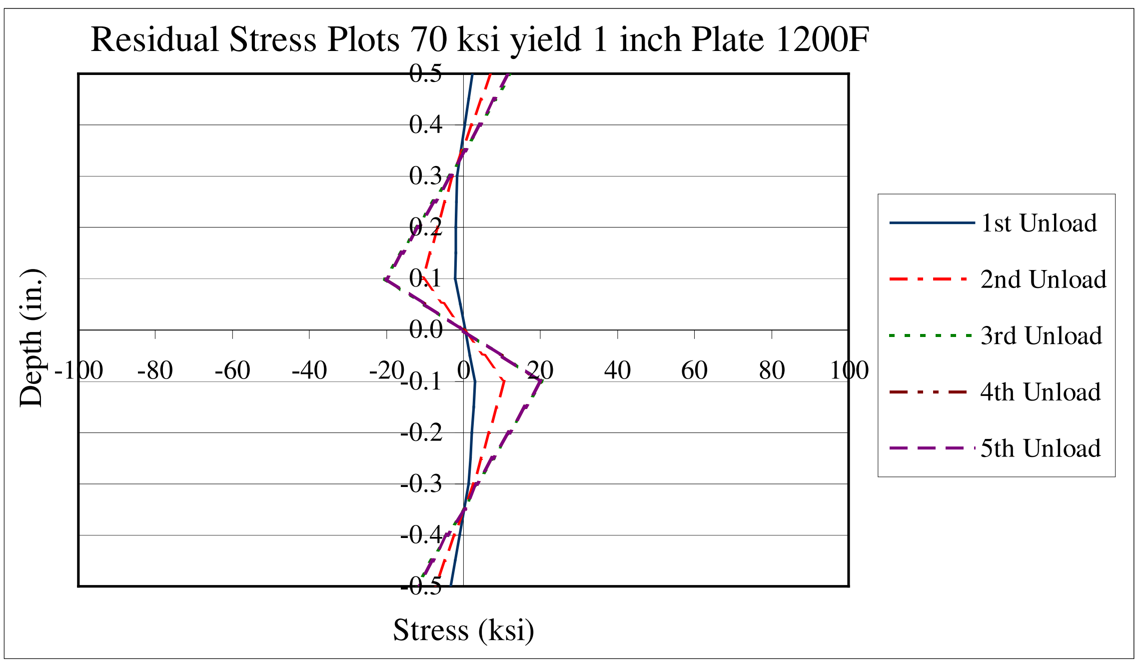

Stress Plots 70 ksi yield 1 inch Plate 5 Minute Cooling
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

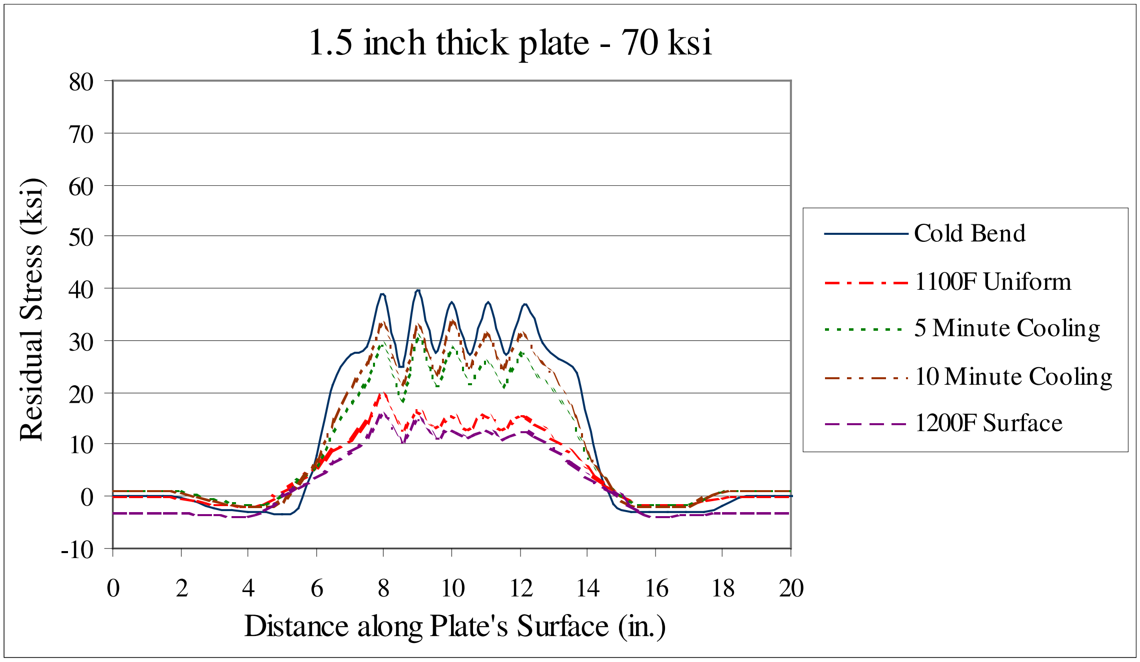

Residual Stress 70 ksi yield 1 inch Plate 5 Minute Cooling
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

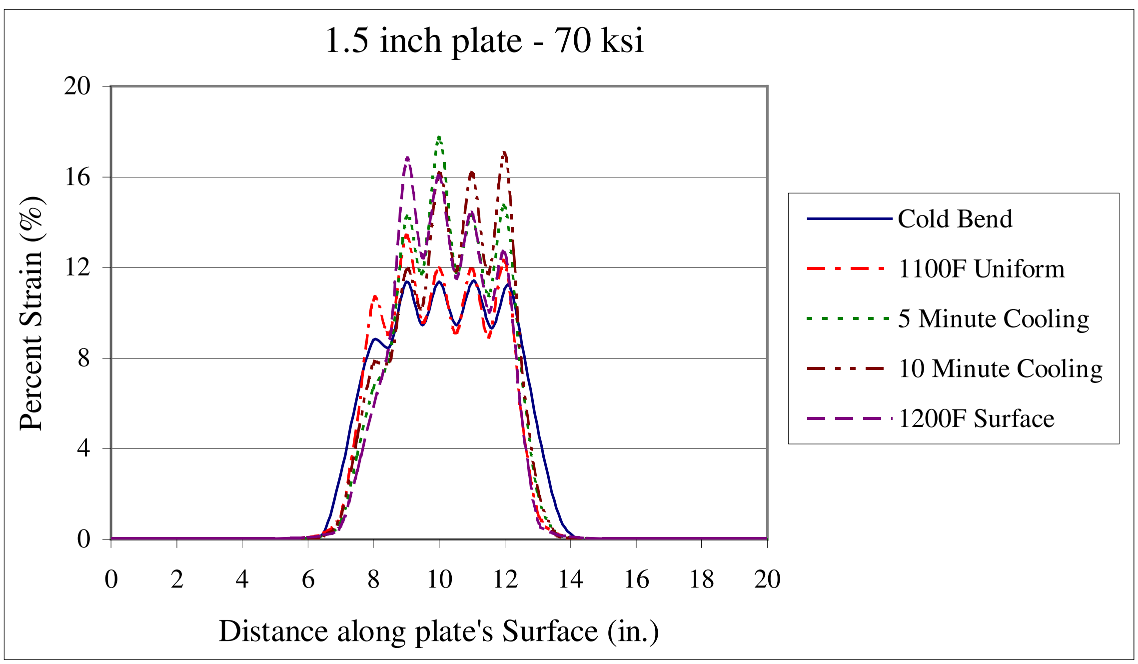

Stress Plots 70 ksi yield 1 inch Plate 10 Minute Cooling
Depth (in.)
Stress (ksi)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-100
-80
-60
-40
-20
0
20
40
60
80
100
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

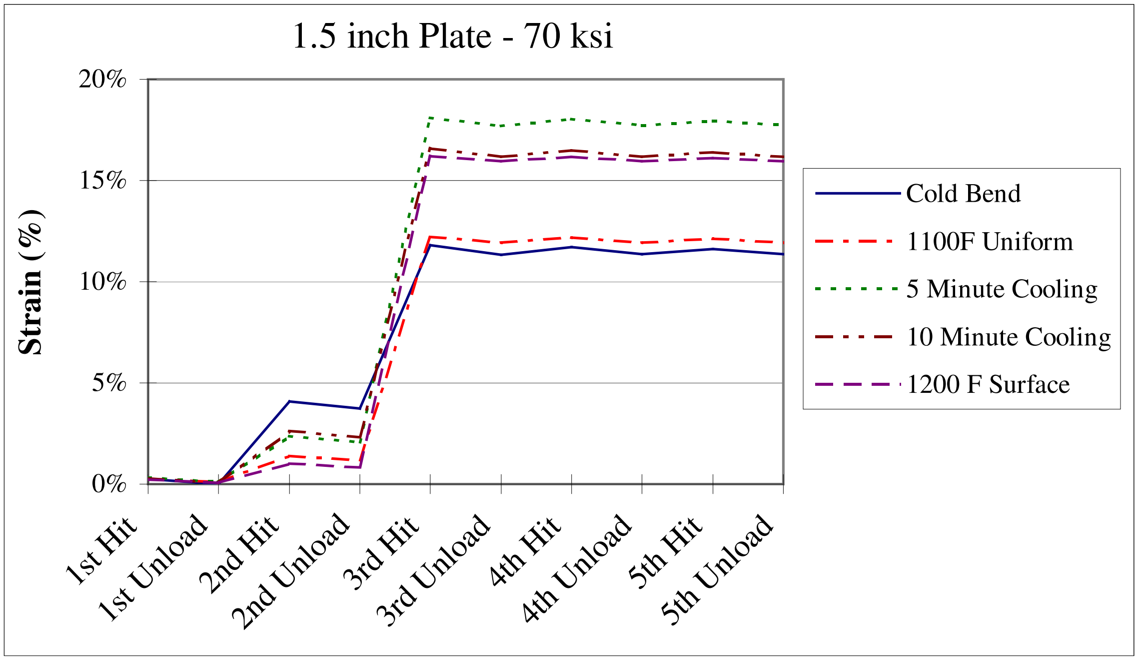

Residual Stress 70 ksi yield 1 inch Plate 10 Minute Cooling
Depth (in.)
Stress (ksi)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-100
-80
-60
-40
-20
0
20
40
60
80
100
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

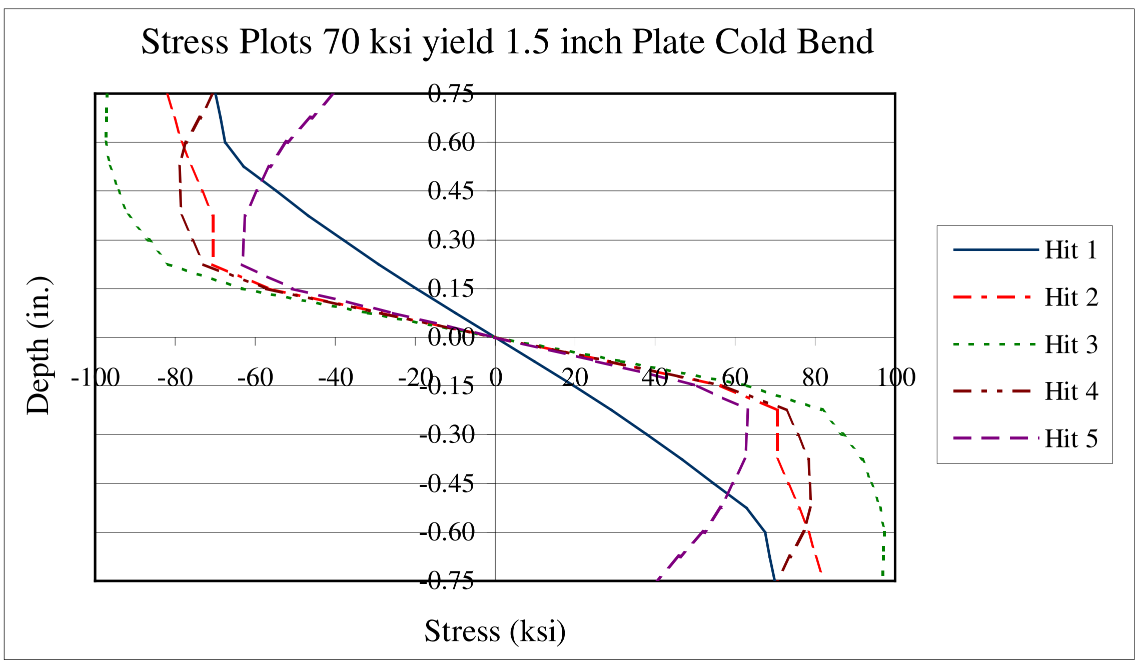

Stress Plots 70 ksi yield 1 inch Plate 1200F
Depth (in.)
Stress (ksi)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-100
-80
-60
-40
-20
0
20
40
60
80
100
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

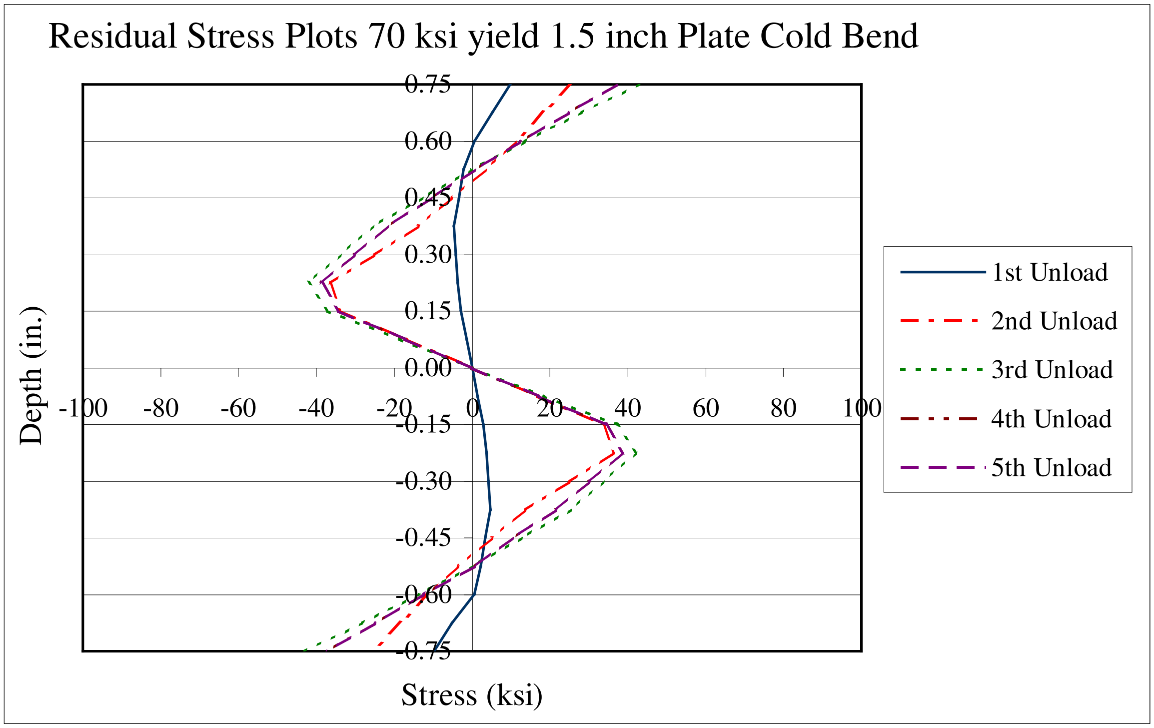

Residual Stress Plots 70 ksi yield 1 inch Plate 1200F
Depth (in.)
Stress (ksi)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-100
-80
-60
-40
-20
0
20
40
60
80
100
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

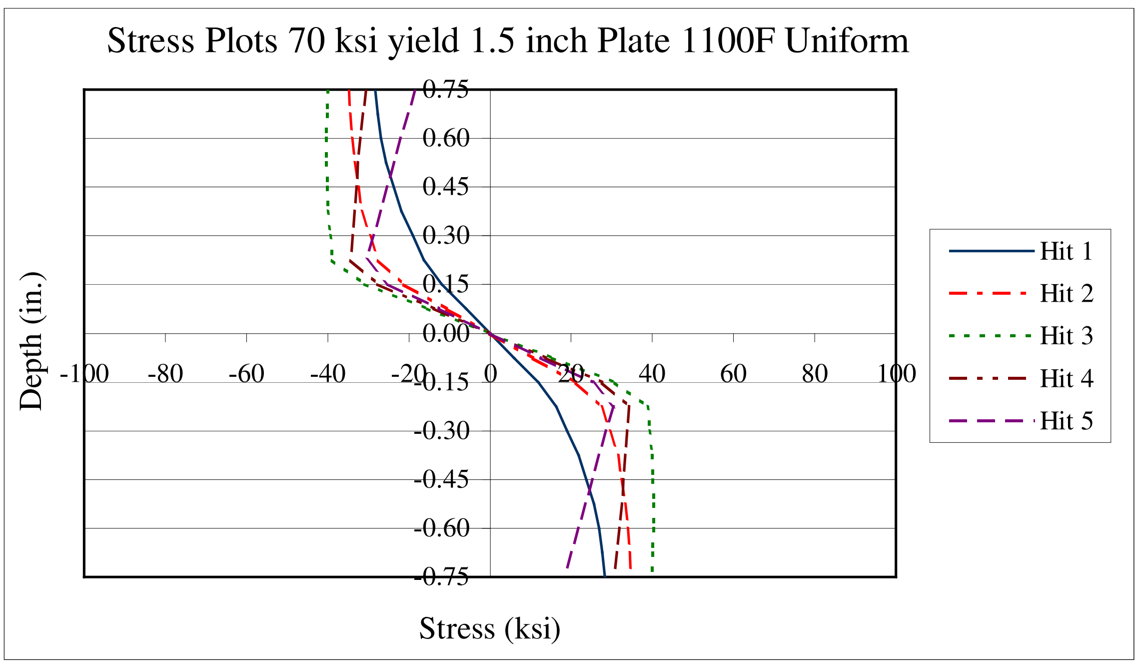

1.5 inch thick plate - 70 ksi
Residual Stress (ksi)
80
70
60
50
40
30
20
10
0
-10
0
2
4
6
8
10
12
14
16
18
20
Distance along Plate's Surface (in.)
Cold Bend
1100F Uniform
5 Minute Cooling
10 Minute Cooling
1200F Surface

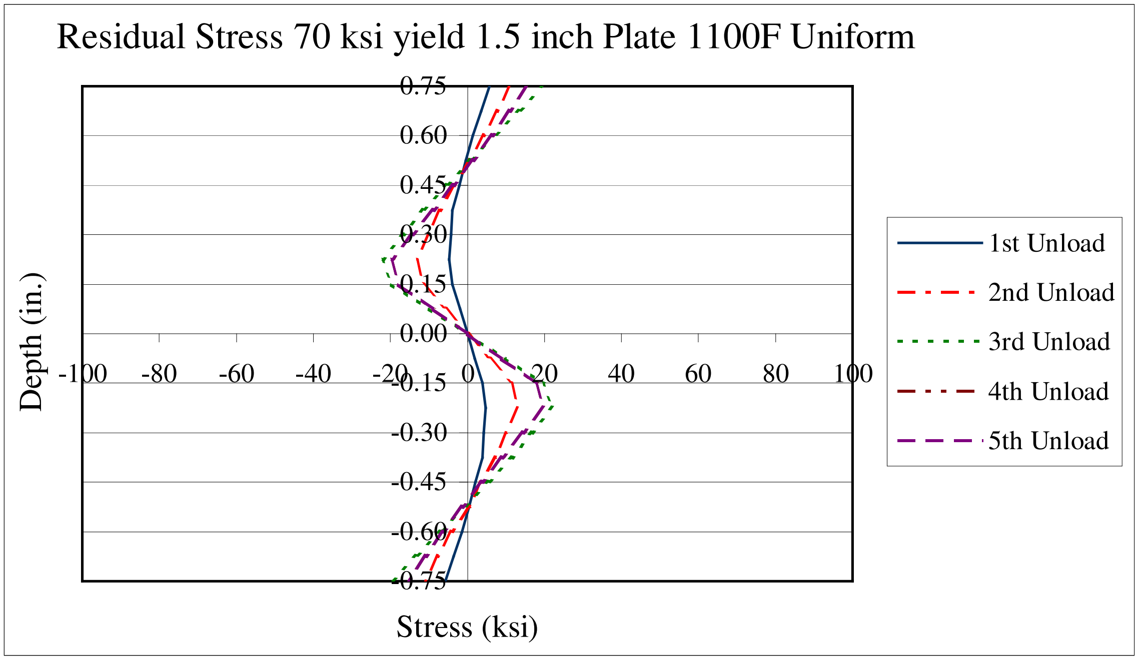

1.5 inch plate - 70 ksi
Percent Strain (%)
20
16
12
8
4
0
0
2
4
6
8
10
12
14
16
18
20
Distance along plate's Surface (in.)
Cold Bend
1100F Uniform
5 Minute Cooling
10 Minute Cooling
1200F Surface

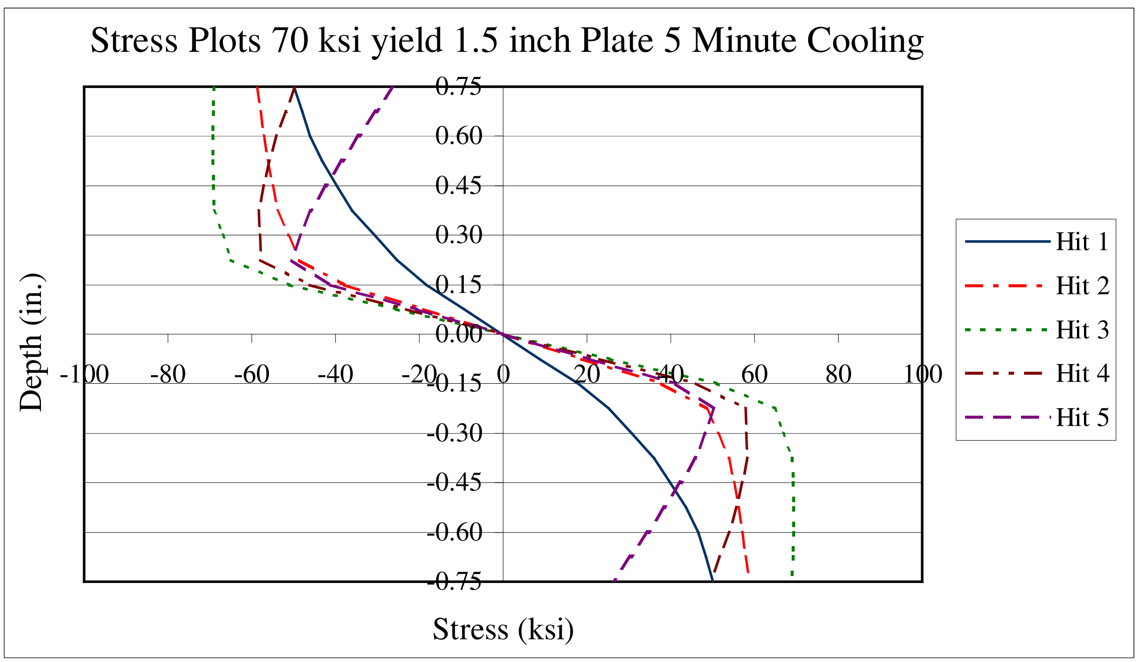

1.5 inch Plate - 70 ksi
Strain (%)
20%
15%
10%
5%
0%
1st Hit
1st Unload
2nd Hit
2nd Unload
3rd Hit
3rd Unload
4th Hit
4th Unload
5th Hit
5th Unload
Cold Bend
1100F Uniform
5 Minute Cooling
10 Minute Cooling
1200 F Surface

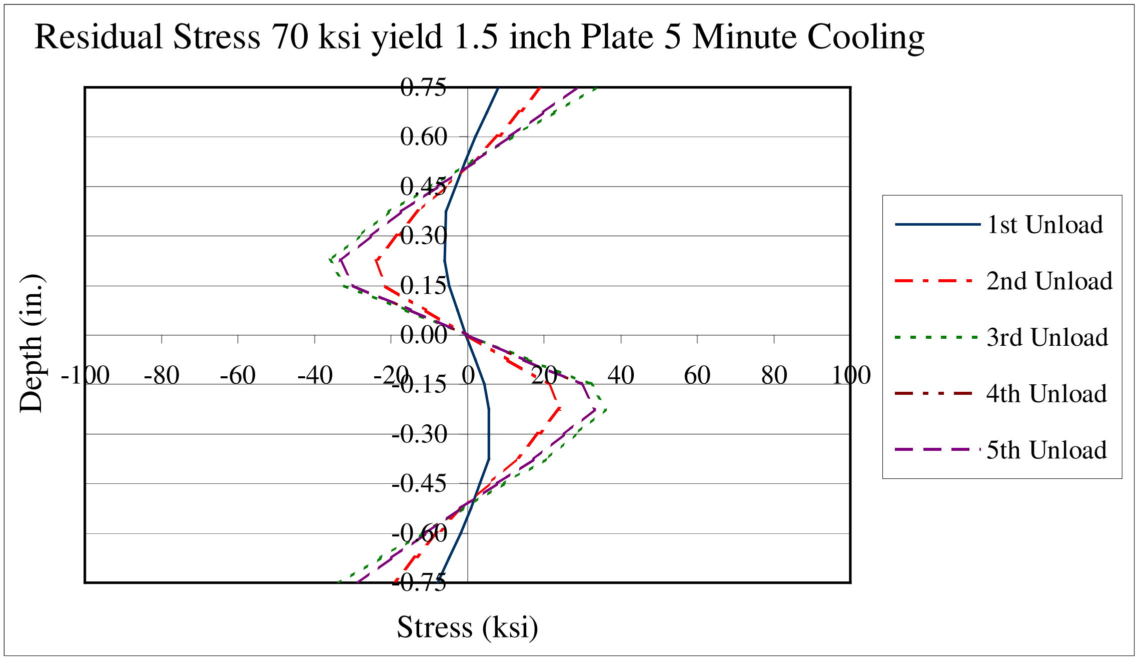

Stress Plots 70 ksi yield 1.5 inch Plate Cold Bend
Depth (in.)
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
Stress (ksi)
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

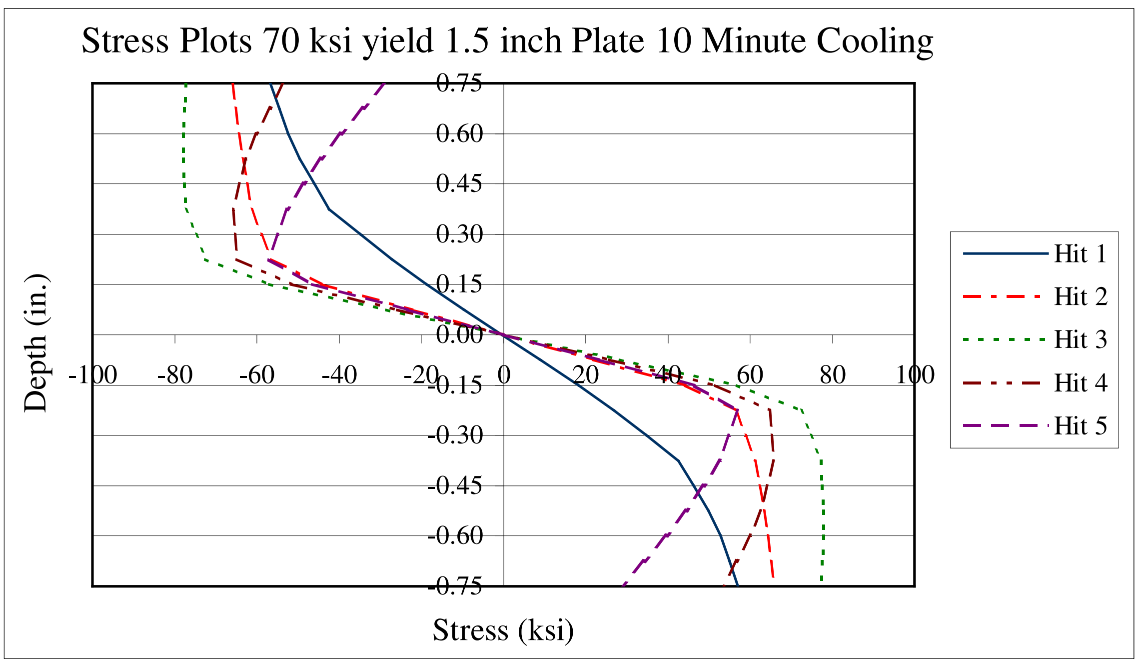

Residual Stress Plots 70 ksi yield 1.5 inch Plate Cold Bend
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

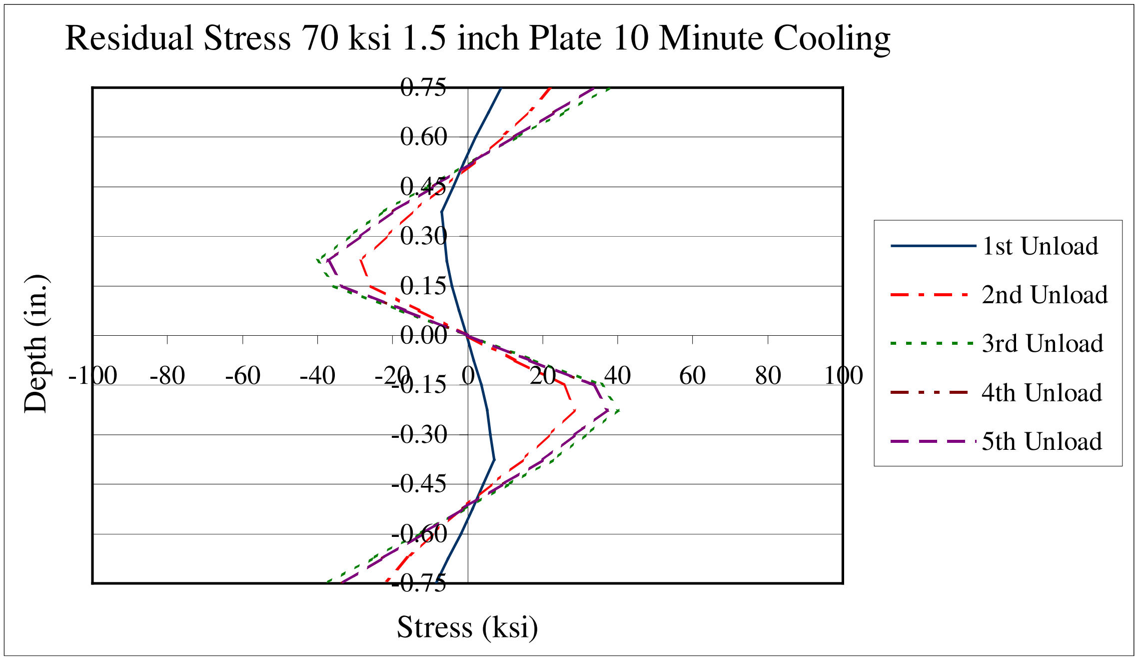

Stress Plots 70 ksi yield 1.5 inch Plate 1100F Uniform
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

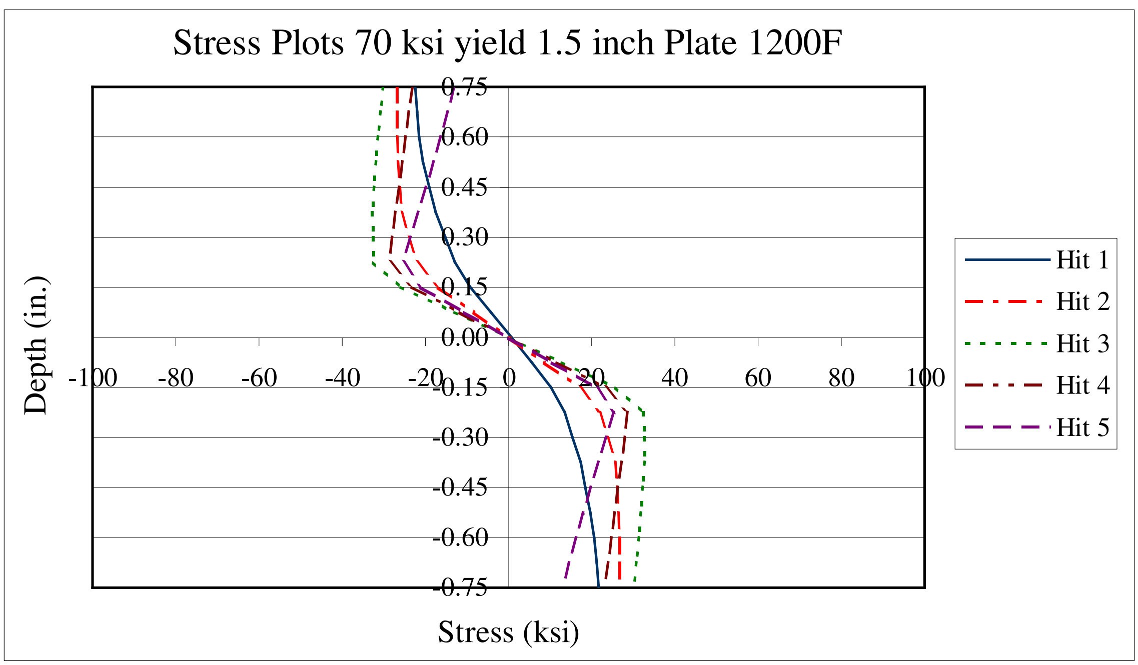

Residual Stress 70 ksi yield 1.5 inch Plate 1100F Uniform
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

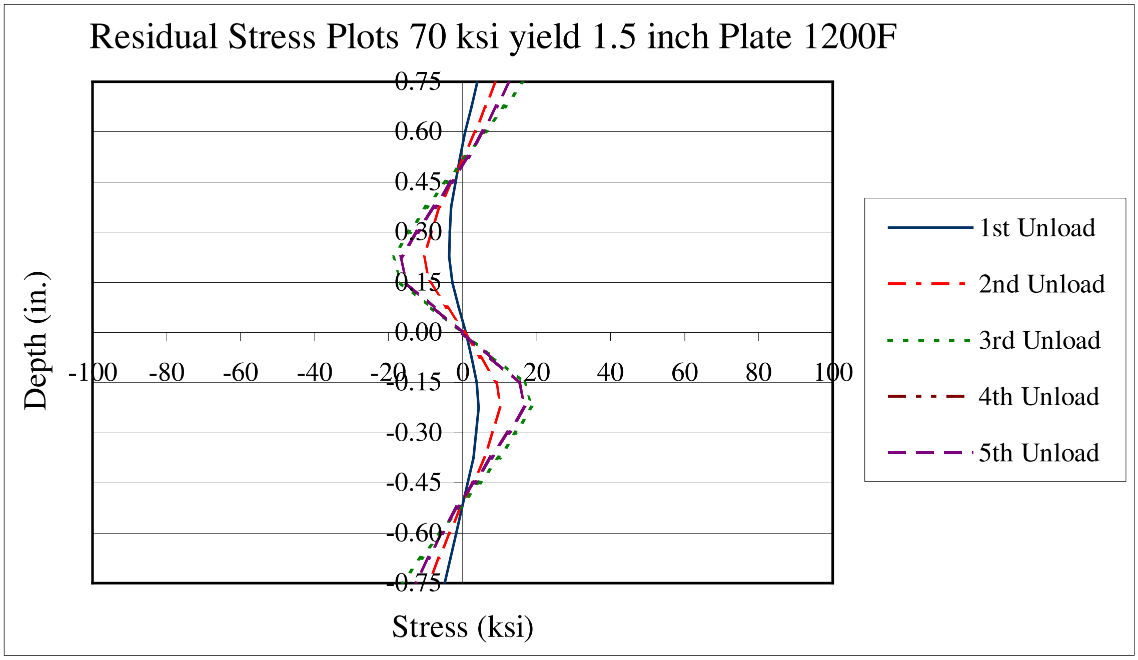

Stress Plots 70 ksi yield 1.5 inch Plate 5 Minute Cooling
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

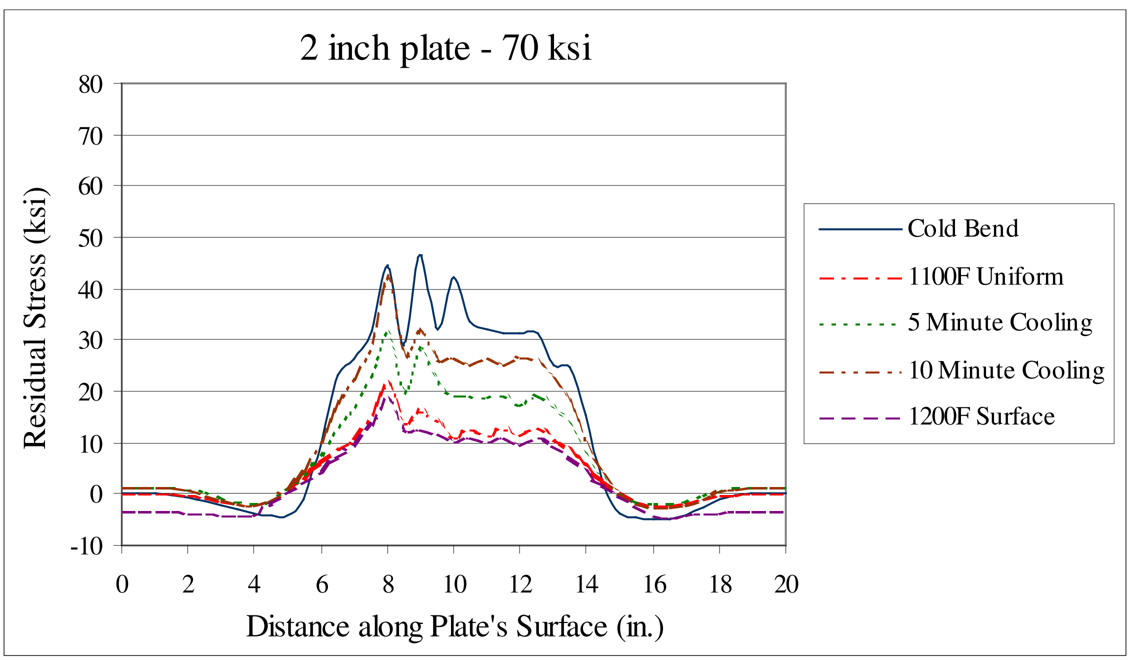

Residual Stress 70 ksi yield 1.5 inch Plate 5 Minute Cooling
Depth (in.)
Stress (ksi)
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

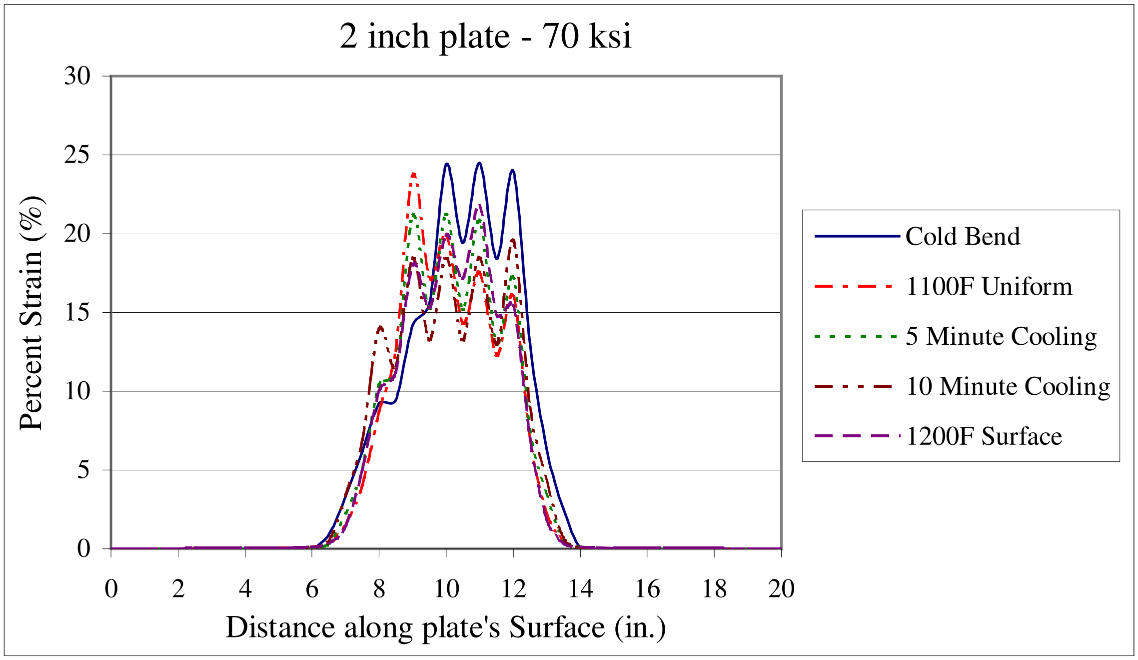

Stress Plots 70 ksi yield 1.5 inch Plate 10 Minute Cooling
Depth (in.)
Stress (ksi)
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5


Residual Stress 70 ksi 1.5 inch Plate 10 Minute Cooling
Depth (in.)
Stress (ksi)
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

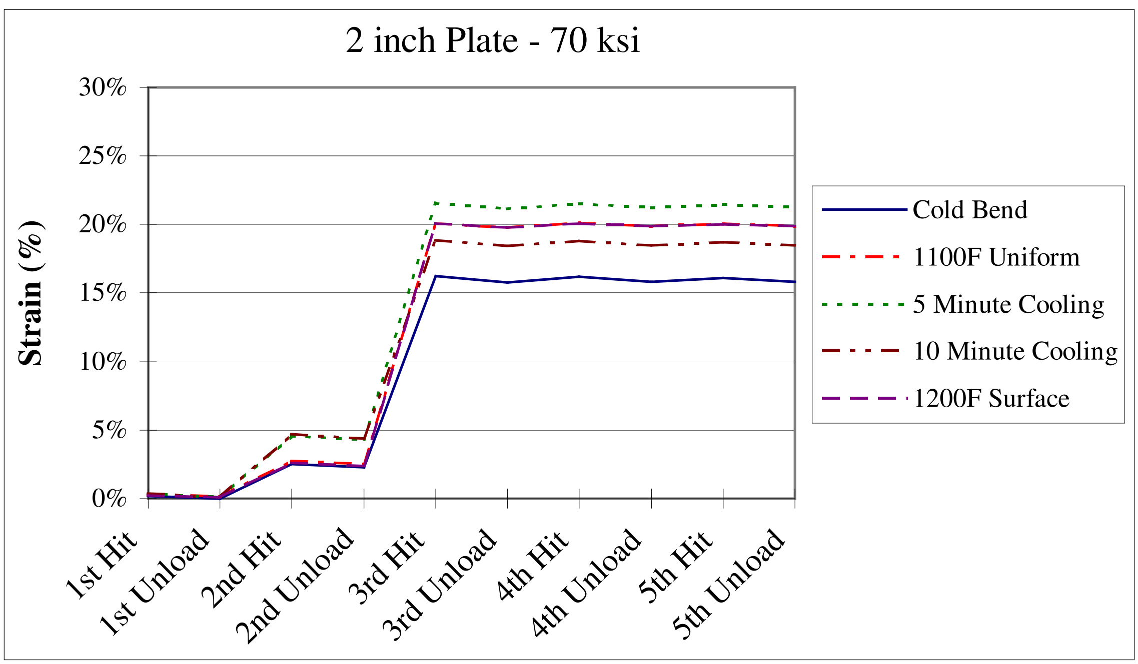

Stress Plots 70 ksi yield 1.5 inch Plate 1200F
Depth (in.)
Stress (ksi)
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5


Residual Stress Plots 70 ksi yield 1.5 inch Plate 1200F
Depth (in.)
0.75
0.60
0.45
0.30
0.15
0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-100
-80
-60
-40
-20
0
20
40
60
80
100
Stress (ksi)
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

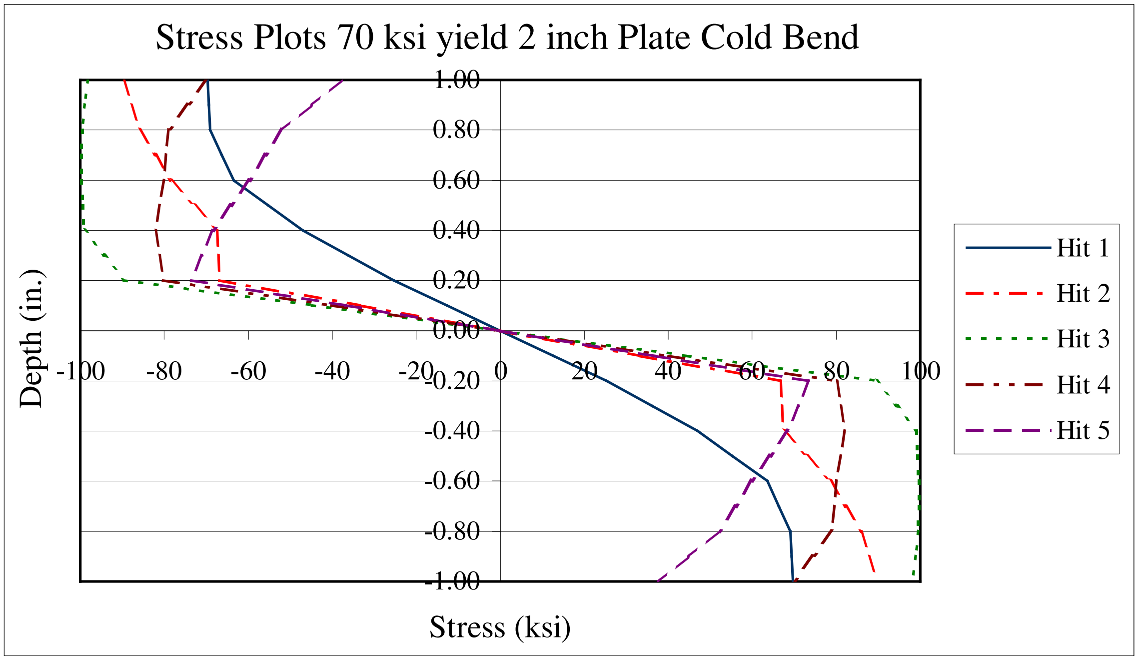

2 inch plate - 70 ksi
Residual Stress (ksi)
80
70
60
50
40
30
20
10
0
-10
0
2
4
6
8
10
12
14
16
18
20
Distance along Plate's Surface (in.)
Cold Bend
1100F Uniform
5 Minute Cooling
10 Minute Cooling
1200F Surface

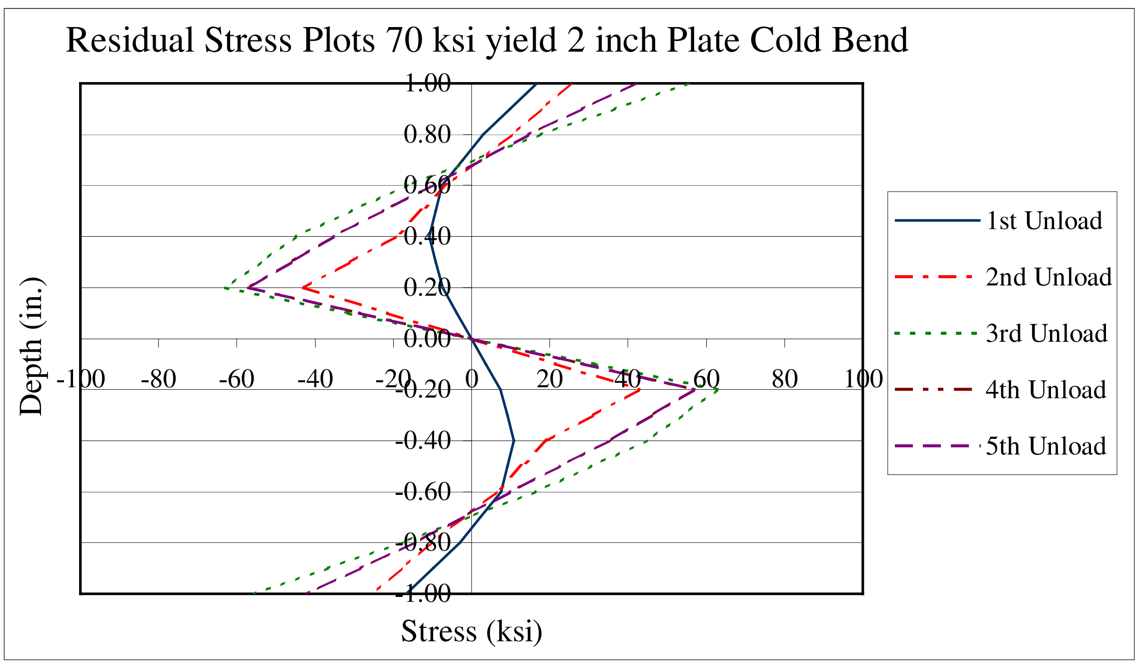


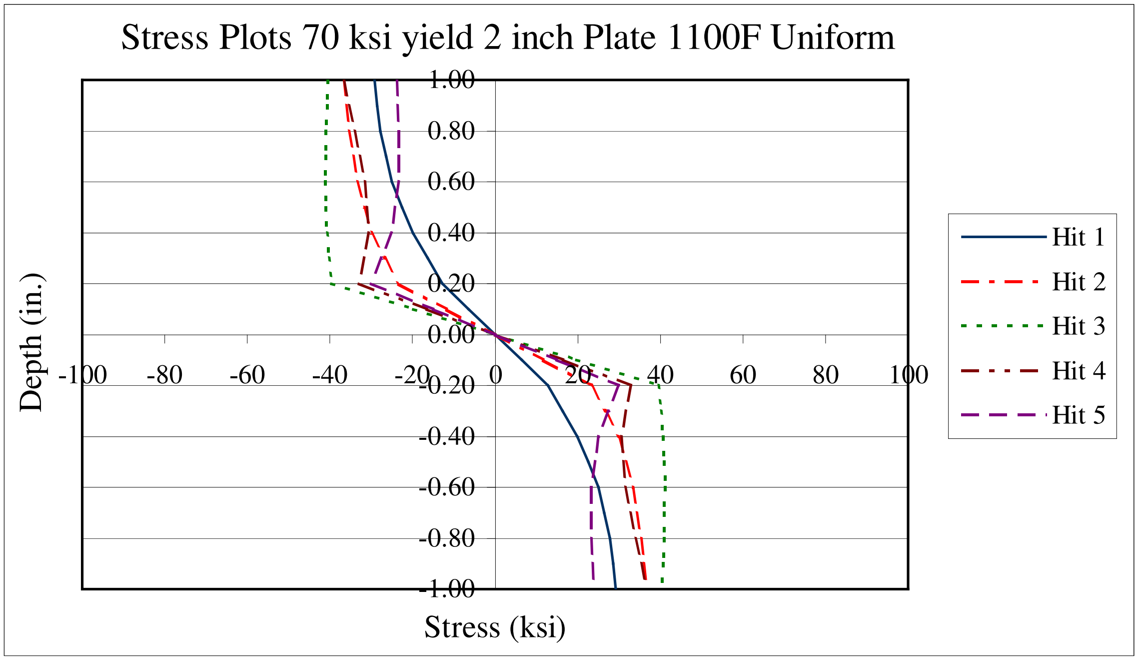
2 inch plate - 70 ksi
Percent Strain (%)
30
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
20
Distance along plate's Surface (in.)
Cold Bend
1100F Uniform
5 Minute Cooling
10 Minute Cooling
1200F Surface

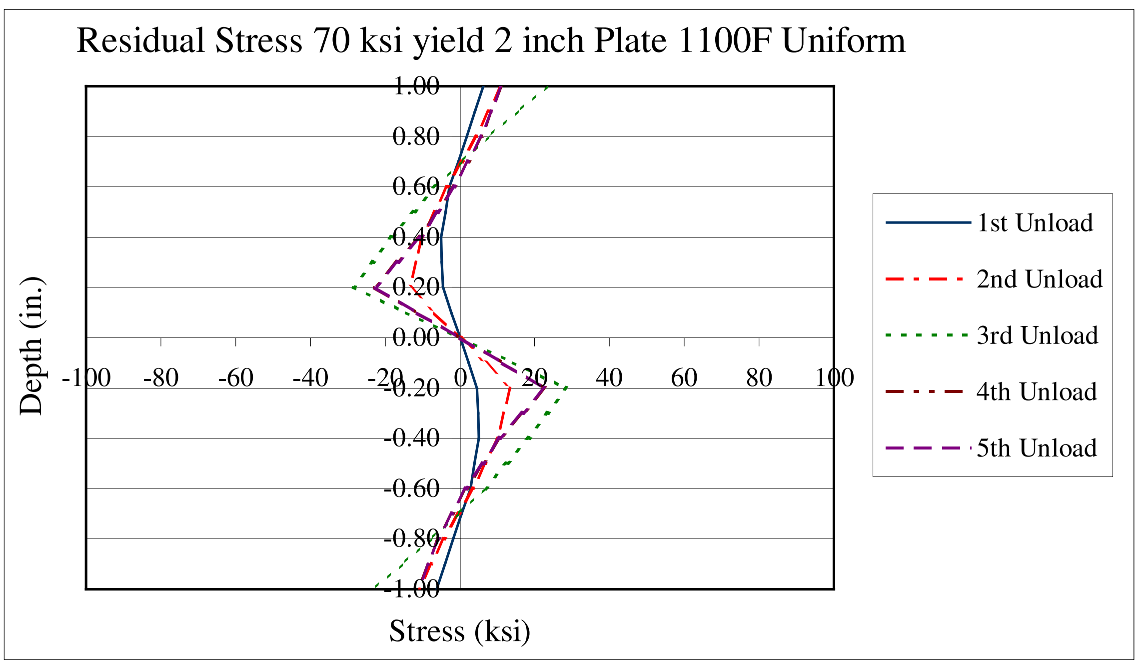


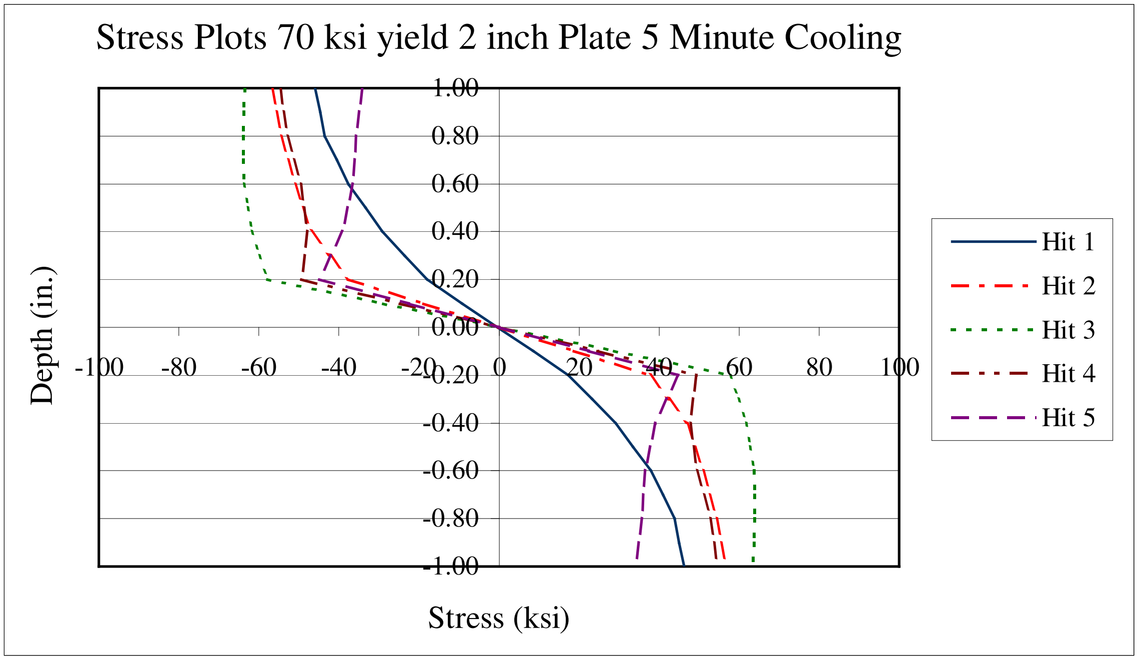
2 inch Plate - 70 ksi
Strain (%)
30%
25%
20%
15%
10%
5%
0%
1st Hit
1st Unload
2nd Hit
2nd Unload
3rd Hit
3rd Unload
4th Hit
4th Unload
5th Hit
5th Unload
Cold Bend
1100F Uniform
5 Minute Cooling
10 Minute Cooling
1200F Surface

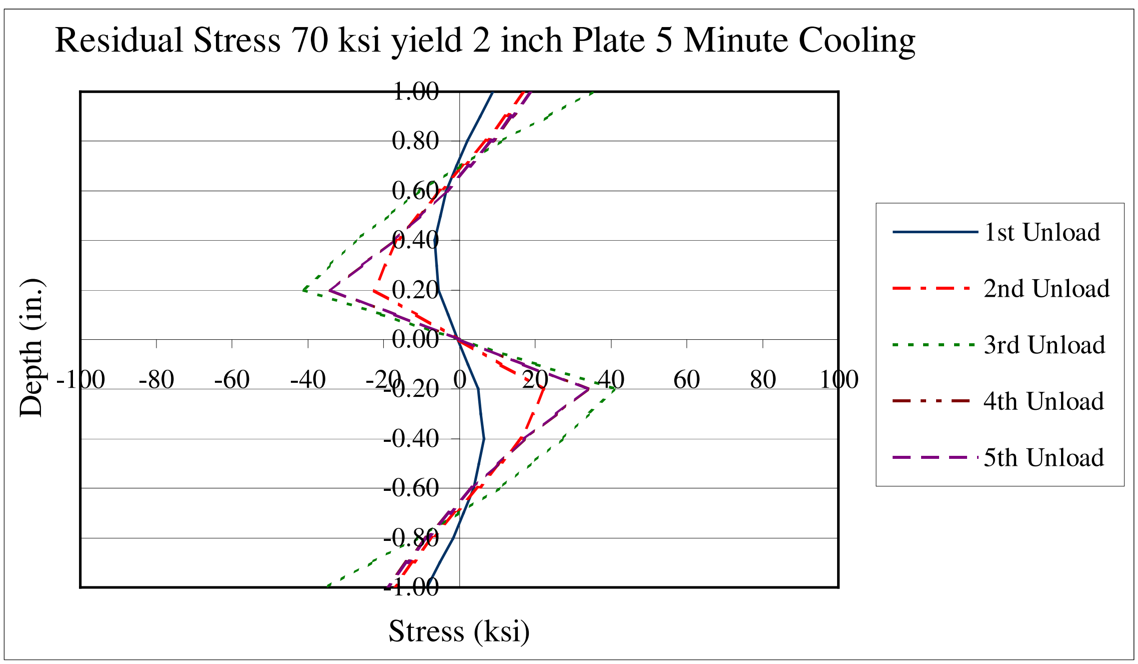

Stress Plots 70 ksi yield 2 inch Plate Cold Bend
Depth (in.)
Stress (ksi)
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

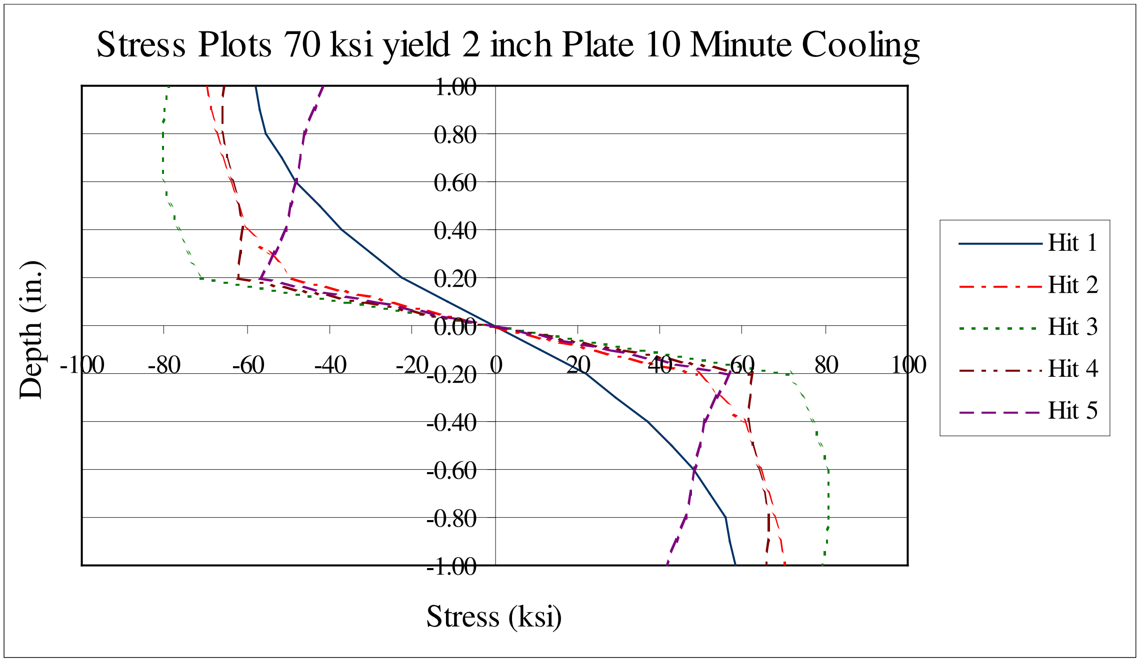

Residual Stress Plots 70 ksi yield 2 inch Plate Cold Bend
Depth (in.)
Stress (ksi)
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

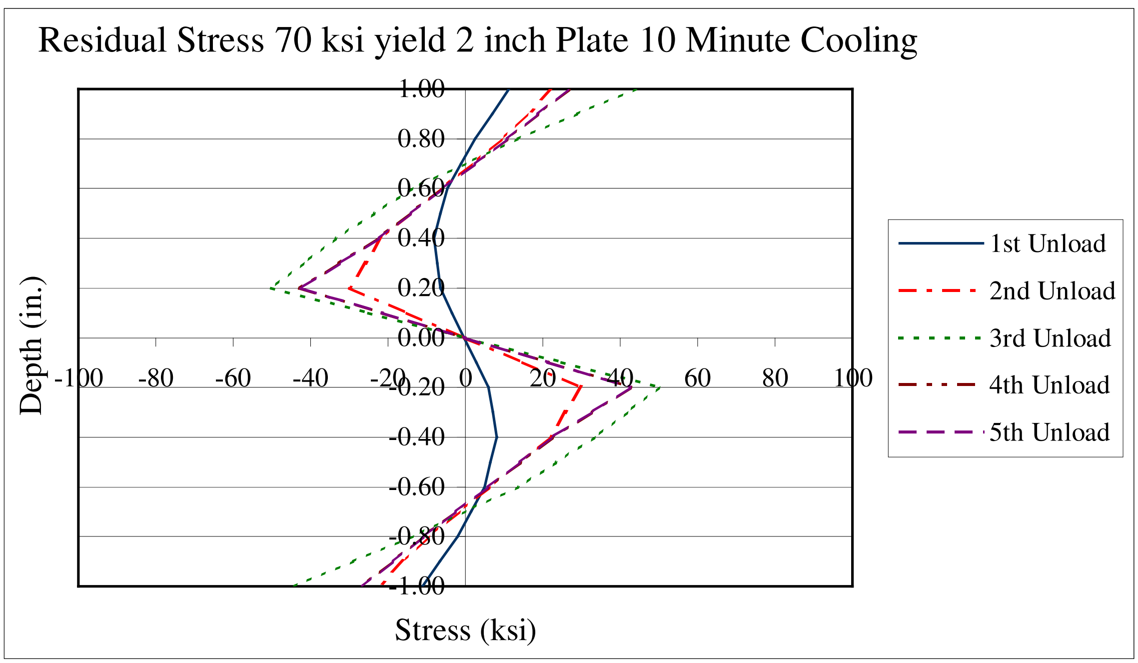

Stress Plots 70 ksi yield 2 inch Plate 1100F Uniform
Depth (in.)
Stress (ksi)
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-100
-80
-60
-40
-20
0
20
40
60
80
100
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5

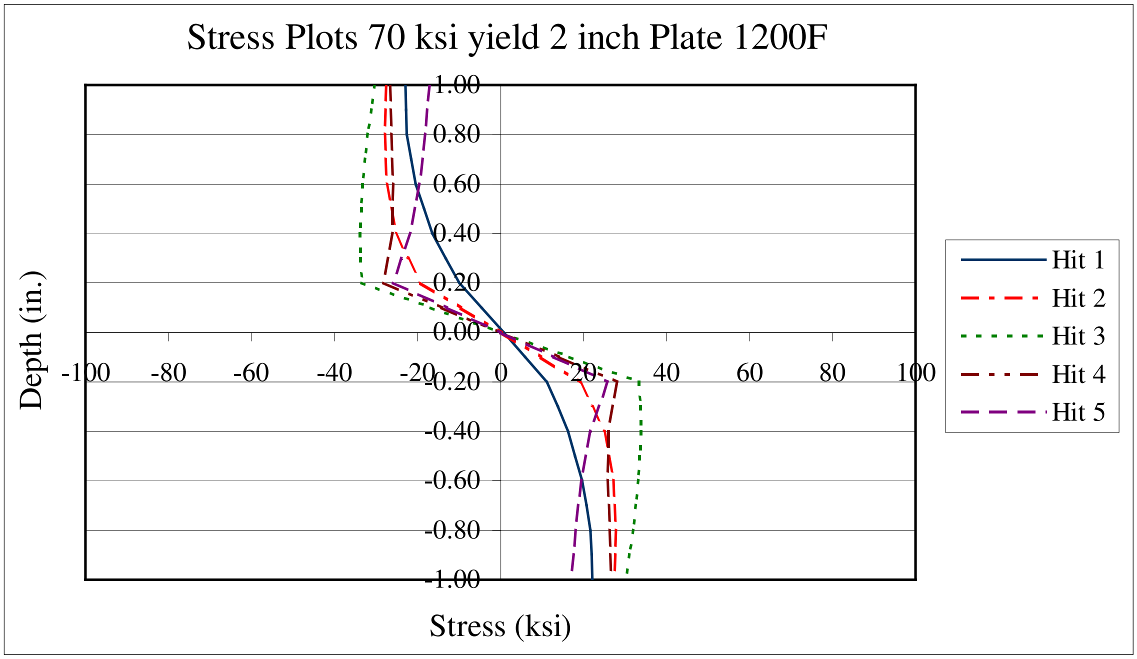

Residual Stress 70 ksi yield 2 inch Plate 1100F Uniform
Depth (in.)
Stress (ksi)
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-100
-80
-60
-40
-20
0
20
40
60
80
100
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

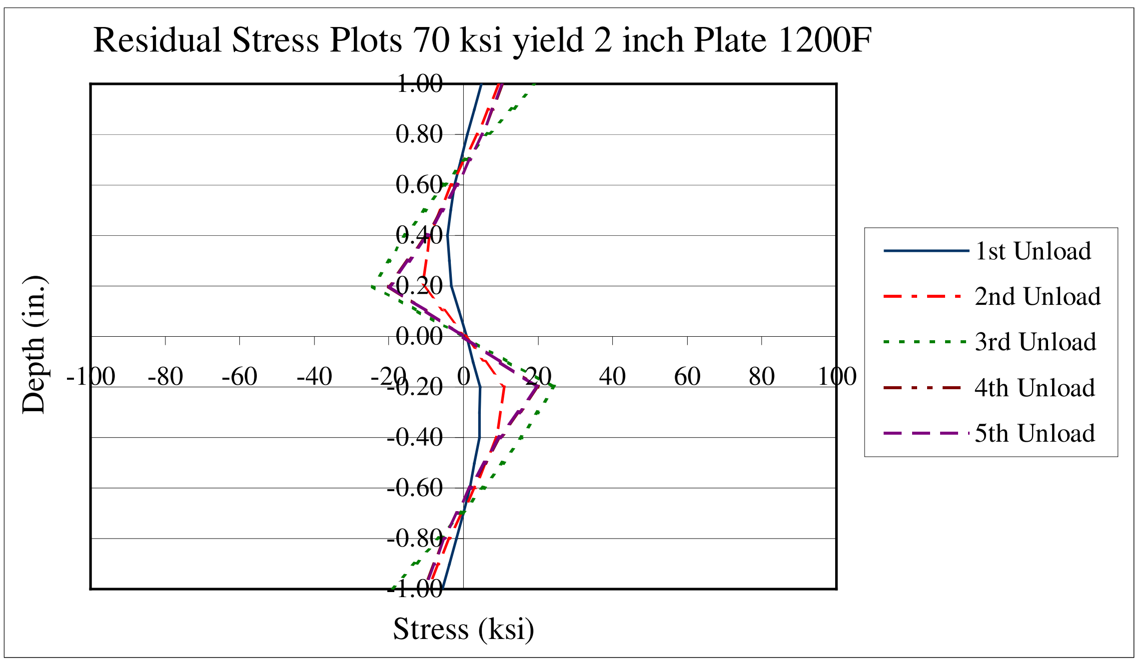

Stress Plots 70 ksi yield 2 inch Plate 5 Minute Cooling
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5


Residual Stress 70 ksi yield 2 inch Plate 5 Minute Cooling
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload


Stress Plots 70 ksi yield 2 inch Plate 10 Minute Cooling
Depth (in.)
Stress (ksi)
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-100
-80
-60
-40
-20
0
20
40
60
80
100
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5


Residual Stress 70 ksi yield 2 inch Plate 10 Minute Cooling
Depth (in.)
Stress (ksi)
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-100
-80
-60
-40
-20
0
20
40
60
80
100
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload


Stress Plots 70 ksi yield 2 inch Plate 1200F
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
Hit 1
Hit 2
Hit 3
Hit 4
Hit 5


Residual Stress Plots 70 ksi yield 2 inch Plate 1200F
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-100
-80
-60
-40
-20
0
20
40
60
80
100
Depth (in.)
Stress (ksi)
1st Unload
2nd Unload
3rd Unload
4th Unload
5th Unload

VITA

Lee Conner Christian received a B.S. in civil engineering form Texas A&M University in May 2003. After receiving a bachelor's degree he then proceeded to obtain an M.S. degree in May 2005 in civil engineering with an emphasis in structures. During the fall of 2003 and spring of 2004 he worked as a student worker on a research project sponsored by the Texas Transportation Institute for determining the standard for the turn-of-the-nut tightening of anchor bolts used in the connections of highway signals. Currently he is working as an engineer for Datum Engineers Inc. He can be reached through his parents at the following address:

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